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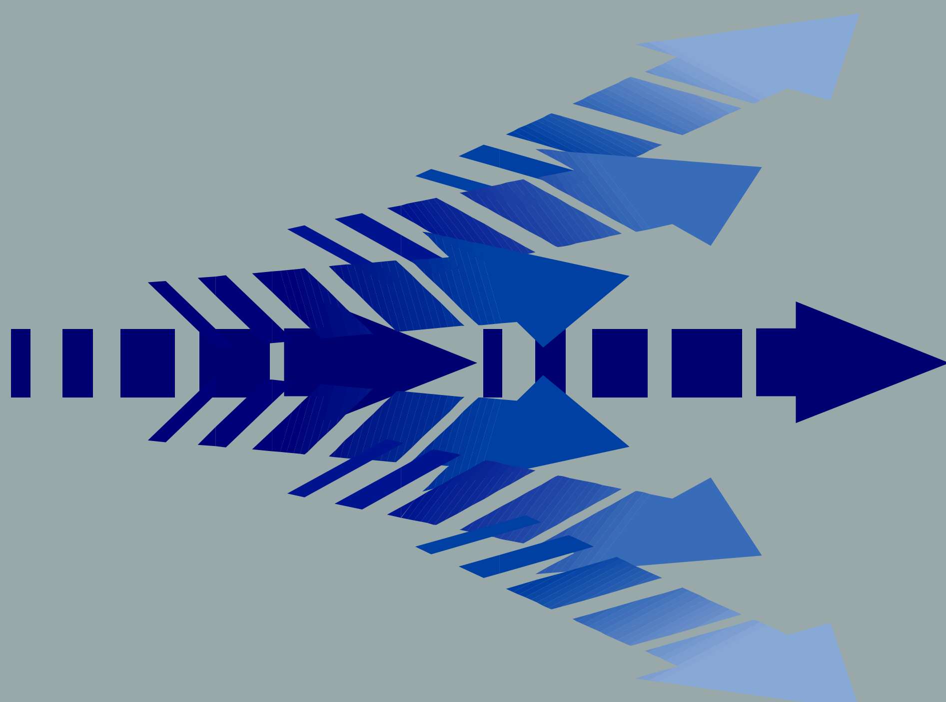
TOOLS FOR RISK BASED ECONOMIC ANALYSIS



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TOOLS FOR RISK-BASED ECONOMIC ANALYSIS

SUMMARY REPORT

February 1999

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TABLE OF CONTENTS

List of Figures

List of Tables

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ACKNOWLEDGMENTS

The model development efforts were carried out under the technical direction of Mr. Michael R. Walsh and Dr. David A. Moser of the Institute for Water Resources, US Army Corps of Engineers. Mr. Walsh and Dr. Moser, as well as serving as technical monitors for the various studies played major roles in data development, model design, user interface design, model testing, and application.

Support for development of the Gulf Intra-Coastal Waterway Model was provided by the Galveston District, under the direction of Mr. Lynwood Weiss, contract manager for the Brazos River to High Island Bends navigation improvement study, and Ms. Gloria Appell, study economist. Development of the Hoover Dike model was supported by funding from the Jacksonville District, under the Herbert Hoover Dike Major Rehabilitation Study, Ms. Kimberly Brooks-Hall, study manager. Mr. Peter J. Grace, Mr. Tom Arnold, and Mr. Danny Peck of the Jacksonville District made large contributions to model development and testing. Both the Galveston and Jacksonville Districts provided important contributions in terms of data development and assistance in problem specification for model design.

Coding of the Hydropower, Lock, and Hoover Dike models was carried out by Planning and Management Consultants, Ltd., Carbondale, Illinois, under the general direction of Craig Strus and Paul York, assisted by Dr. Richard M. Males, RMM Technical Services, Inc., Cincinnati, Ohio. Greeley-Polhemus Group, West Chester, PA, was overall contractor for development of the GIWW model, under the direction of Dr. Charles Yoe, with project participants RMM Technical Services, Inc., and J.E. Edinger and Associates, Wayne, PA (Mr. Edward Buchak, project manager). Model coding was done by RMM Technical Services, Inc., and Chien-Cheng Chen of J.E. Edinger and Associates.

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EXECUTIVE SUMMARY

The Institute for Water Resources (IWR) of the US Army Corps of Engineers, through research and partnership with Corps Districts, has developed a set of tools and techniques to support risk-based economic evaluations involving decisions related to major rehabilitation and maintenance investments.

Desktop computer models have been developed and applied in the areas of:

- Rehabilitation of hydropower facilities
- Rehabilitation of navigation locks
- levee/dike performance
- Commodity transport on waterways.

The models provide a framework for developing and storing required data, performing the needed calculations, evaluating results, and comparing with- and without-project alternatives from a benefit/cost perspective. The models are more general, easier to use and understand, and significantly faster than previously available methods, and can easily be directly applied or adapted to many problems.

IWR developed the suite of models to implement complex simulation solutions in as simple a manner as possible, consistent with the nature of the problem under analysis. All of the models share a common approach and architecture. Experience in development and application of these models has provided IWR with a strong background, experience, skill and tool set in dealing with problems associated with risk-based analysis of investment decisions.

Four models have been developed to date:

1) Hydropower REPAIR

This model simulates the economic behavior of a hydropower generating facility over a life cycle (typically 50 years), for purposes of determining the advisability of major rehabilitation investments. The facility is composed of generating units, which are composed of components (typically, a turbine and generator), whose operating status determines the output of the facility. Components can degrade and perform unsatisfactorily, based on input hazard functions giving the probability of unsatisfactory performance as the component ages. Rehabilitation is directed at the component, and reduces the probability of unsatisfactory performance over time. The model calculates present values of benefits of operation, repair costs for components that degrade during the simulation time period, operation and maintenance costs, and rehabilitation costs. Several Corps District offices, most recently the Omaha District for the Garrison project have used this model to evaluate hydropower rehabilitation proposals.

2) Life Cycle Lock Repair Model

The Life Cycle Lock Model (LCLM) is used to analyze investments at a single lock (consisting of one or two lock chambers). Each chamber is composed of user-defined components (e.g. control system, miter gates, etc) which can be in any one of a range of user-defined states. Tows arrive at the lock randomly, based on user input statistics, form queues, and are serviced by the lock, with the service time determined by the state of lock components. Components can degrade based on user-entered state transition probabilities. Repairs, with associated user-defined cost and duration, result in returning the component to another of the allowable states. Rehabilitation alternatives are defined by setting component states at a particular time within the simulation, in conjunction with a user-entered rehabilitation cost schedule.

Model output provides information on total repair costs, rehabilitation costs, and delay costs based on tow transit time, together with benefit/cost comparisons of with- and without-project alternatives.

3) Levee Repair Model

Developed in conjunction with the Jacksonville District, a model of Herbert Hoover Dike surrounding Lake Okeechobee provides analysis of rehabilitation alternatives through a life cycle simulation of dike performance in response to changing lake stages and hurricane surge. The dike is composed of contiguous areas (components) of similar geotechnical behavior. Lake stage is probabilistic, based on statistical models developed from historical data, with additional probabilistic storm surge associated with hurricanes. Hazard functions are defined for each dike component, giving the probability of breaching as a function of lake stage. Damages accrue based on flooding associated with breaching of components. The model handles multiple land uses, degree of flooding, monetary and non-monetary damages, and consequences of repeated flooding, as well as repair and rehabilitation costs, providing detailed and summary output on benefits and costs. The model is currently being used in conjunction with the Herbert Hoover Dike Major Rehabilitation Evaluation, and should be readily adaptable to other related problems, such as dam safety analysis or river levee systems.

4) Waterway System Simulation

In association with the Galveston District, a waterway simulation model was developed for use in a study of maintenance alternatives on a portion of the Gulf Intra-Coastal Waterway (GIWW) around Galveston. The model simulates the movement of individual tows from port to port on a waterway network, defined as a set of reaches. Maintenance and rehabilitation investments reduce travel time in a particular reach at a specified cost, and benefits accrue as reduction in total travel time for the system. The model accounts for each tow movement on the waterway, and handles traffic rules and congestion in waterway reaches. The model is general in nature, with user definition of the waterway, tow distribution, port-to-port shipment statistics, transit times and rules in each reach. Uncertainty is incorporated through the port-to-port shipments and reach transit times, which are defined by statistical distributions. As with the other models, detailed output allows for examination of individual tows and reaches, and summary output provides benefit and cost analyses. The model has been applied on the High Island to Brazos River portion of the GIWW, and will be used in subsequent additional studies.

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I. INTRODUCTION

This report contains a summary description of research and development efforts carried out at the Institute of Water Resources, US Army Corps of Engineers (Corps), relating to the development of software tools (models) for risk-based analysis. Work was initiated in December of 1992, and through a series of related research efforts and projects assisting districts, IWR has evolved a strong base of knowledge, skills, tools, and experience for dealing with risk-based planning analysis. Based on this experience, four distinct models have been developed. The purpose of this report is to explain the purpose, background, and history of the work effort; the underlying general concepts used in all models; and the structure and approach of each of the four models developed to date.

CORPS INTEREST

The Corps operates and maintains some 300 locks and dams, 350 flood control structures, and 75 hydropower projects across the nation representing billions of dollars of capital investment. As these projects age, the Corps is faced with the prospect of maintaining and rehabilitating the civil works structures and equipment needed to provide navigation, flood control, hydropower and other water resources benefits to the nation. With a budget exceeding 1.5 billion dollars a year for operation and maintenance of Corps facilities, large sums of money are involved.

In an era of increasingly limited budgets and resources it is imperative that investment decisions for Corps projects be made wisely and on a sound technical basis. With new construction limited due to budgetary constraints, recognition of environmental impacts, and requirements for cost sharing, the ability to gain efficiency and reliability improvements in existing projects through rehabilitation and maintenance has become increasingly important.

Over time, the Corps has developed policies, procedures and guidelines to insure technical correctness, consistency, and completeness in making investment choices. Since the late 1970's, the concept of risk analysis has been embodied in many of the Corps' decision processes. Risk analysis recognizes the inherent variability associated with many physical and socio-economic processes, and attempts to account for this variability in a systematic manner. Risk-based approaches are increasingly being recognized as the technically correct and appropriate method for examining a broad range of engineering and planning problems, and requirements for risk-based economic analysis have been specifically incorporated into Corps guidance for major rehabilitation studies.

IWR RESEARCH PROGRAM

IWR has a long history of involvement in development of planning methodologies and approaches for the Corps. Many of the techniques are widely used in other arenas as well. In 1991, IWR initiated a joint research program with the Waterways Experiment Station and the Hydrologic Engineering Center for examination of Risk Analysis for Water Resources Investments.

In 1992, IWR published the first volume of the "Guidelines for Risk and Uncertainty Analysis in Water Resource Planning", describing the general process of using risk analysis in planning evaluation. IWR has been a strong proponent of the use of risk-based analytical techniques within the Corps, and has developed a series of research initiatives in this arena.

IWR developed and regularly conducts a training course on the use of risk analysis, and provides support to other Corps organizations, cooperating with Districts on a variety of projects. IWR has thus become a center of expertise within the Corp relating to risk-based economic analyses.

IWR has also undertaken research initiatives examining the use of advanced software tools for decision-making support. Recognizing the joint needs of: embodying risk-based analysis methodologies in specific, readily usable technologies; providing tools to assist Districts; and developing tutorial methods associated with training, IWR initiated in 1993 a series of research efforts to develop software implementing risk-based methods. Over time, additional tools have been developed to support Districts on specific projects, drawing on the technologies developed under the Research Program.

NEED FOR ANALYSIS TOOLS

Investment problems involving risk-based analysis are typically complex, requiring assessments of the important elements of variability of the physical and economic systems under study. This can require a multi-disciplinary effort, at minimum, expertise in engineering, economics, and statistical methods.

Corps guidelines mandate the use of risk-based economic analysis for major rehabilitation studies, but do not prescribe exact methods. Thus, a variety of applications of risk-based techniques have been developed for particular studies and investigations, with different degrees of complexity and sophistication. There is duplication of effort, as similar problems are handled individually, on a case- and site- specific basis. There is little uniformity in the techniques used and the particular risk elements included, even for comparable problems. The techniques used may not be easily understood, with little documentation, and can be difficult to assess in terms of technical correctness, leading to problems in the review process. Risk-based analysis is relatively new within the Corps, and experience with the methodologies is still evolving. Thus, even where tools have been developed, there is no guarantee that they will be appropriately applied.

Many of the problems addressed by risk analysis are similar in nature (rehabilitation of hydropower facilities or navigation locks), and require similar techniques (statistical analysis, generation of random numbers, etc.) Thus it is desirable to develop consistent, efficient, technically correct, easily used, and well-documented approaches which can be applied across a range of problems, and integrated into the decision process at an early stage. Over time, a body of experience can be built up around standard techniques, leading to greater transferability and ease of use.

Existing tools are generally custom spreadsheet-based analyses, developed on a site-specific basis to serve the needs of a particular study. Development of such tools requires a significant learning curve. Spreadsheet tools tend to be slow to operate, and difficult to parameterize. As such, it is less likely that they will be used appropriately. Further, such tools are difficult to evaluate and review externally.

Given the similarity of problems, the unfamiliarity of the technology to many, and the difficulty of insuring that a particular tool has been developed and applied correctly, there is great value in developing a set of risk-based analysis tools that can be used across a number of projects.

PROJECT HISTORY

The overall project has been accomplished through a series of research initiatives, starting in December of 1992 with a study to develop a general-purpose tool for analysis of major rehabilitation investments. The initial application was oriented towards hydropower facilities, but the tool was originally envisioned as being more general in nature, applicable to any facility-based rehabilitation problem.

A subsequent examination of major rehabilitation for navigation locks showed that the nature of that problem was sufficiently distinct from the hydropower formulation to warrant development of an independent model, initiated in May of 1994. From that time, it was recognized that a general-purpose model would not be appropriate for all risk-based problems, but that certain common approaches could be used to develop problem-specific models. These problem-specific models could be used for a particular class of problem (e.g. a hydropower facility, or a navigation lock), and applied to specific projects through specification of input data. This approach has been carried out in subsequent development.

Additional development of the Hydropower REPAIR and Life Cycle Lock Repair Models proceeded on separate but related paths, with continual improvements to the underlying techniques and software. The final version of the Hydropower REPAIR model was developed in September 1997, and the Life Cycle Lock Repair Model was completed in June of 1998.

During the course of the research efforts on the Hydropower REPAIR and Life Cycle Lock Repair models, IWR assisted the Jacksonville District in the construction of a risk-based model for major rehabilitation of the Herbert Hoover Dike surrounding Lake Okeechobee. The Hoover Dike problem was recognized as yet another type of problem, and was developed specifically for the Hoover Dike rehab study, but with a view towards more general application. Thus, as with the other two models, it is specified to the Hoover Dike situation through user setting of input data. Development of this model was initiated in January of 1997, and completed in July of 1998.

IWR also assisted the Galveston District in developing a tool to be applied in a series of studies of improvements to the Gulf Intra-Coastal Waterway (GIWW), starting with a study of the portion of the waterway from High Island to the Brazos River, in the Galveston area. This led to the development of yet another class of risk-based model, oriented towards vessel movements on a waterway system. Again, the model was developed in the context of the specific project study, but is general in nature. Work was initiated in February of 1997, and the model was completed and applied to the GIWW study in April of 1998.

APPLICABILITY OF TOOLS

The tools developed to date are designed primarily for assessments of rehabilitation and/or maintenance investments that improve reliability and/or performance of physical components. In some cases, the impact of different types of operating or maintenance policies can also be examined.

The typical analysis is a comparison of a baseline situation, representing the as-is behavior of the system under study, with one or more with-project alternatives. Thus, the tools are not oriented towards assessing the benefits of new construction, but rather towards changes made to existing systems. The primary output measures associated with the models are largely economic in nature, for purposes of analysis of NED benefits. In addition, some of the models provide other outputs that can be used as surrogates for safety and loss of life. The models do not, at this time, incorporate directly any environmental impacts.

These tools can be used to meet the requirements for risk-based economic analysis set forth in the following Engineer Regulations and Engineering Circular:

> Partners and Support (Work Management Guidance and Procedures), December 1996. EP 1130-2-500. U.S. Army Corps of Engineers, Washington, DC.
>
> Engineering and Design - Risk-Based Analysis in Geotechnical Engineering for Support of Planning Studies, February 1998. EC 1110-2-554. U.S. Army Corps of Engineers, Washington, DC.
>
> Risk-Based Analysis in Geotechnical Engineering for Support of Planning Studies, February 1998. EC 1110-2-554. U.S. Army Corps of Engineers, Washington, DC.

Engineering and Design - Introduction to Probability and Reliability Methods for Use in Geotechnical Engineering, September 1995. ETL 1110-2-547. U.S. Army Corps of Engineers, Washington, DC.

Engineering and Design - Reliability Analysis of Navigational Lock and Dam Mechanical and Electrical Equipment, November 1997. ETL 1110-2-549. U.S. Army Corps of Engineers, Washington, DC.

Engineering and Design - Reliability Assessment of Navigation Structures, May 1992. ETL 1110-2-532. U.S. Army Corps of Engineers, Washington, DC.

Engineering and Design – Reliability Assessment of Pile-Founded Navigation Structures, August 1995. ETL 1110-2-354. U.S. Army Corps of Engineers, Washington, DC.

Engineering and Design – Uncertainty Estimates for Nonanalytic Frequency Curves, October 1997. ETL 1110-2-537. U.S. Army Corps of Engineers, Washington, DC.

Reliability Assessment of Existing Levees for Benefit Determination, March 1993. ETL 1110-2-328. U.S. Army Corps of Engineers, Washington, DC.

Reliability Assessment of Navigation Structures Stability of Existing Gravity Structures, December 1993. ETL 1110-2-321. U.S. Army Corps of Engineers, Washington, DC.

Life Cycle Design and Performance, October 1997. ER 1110-2-8159. U.S. Army Corps of Engineers, Washington, DC.

Policy and Planning - Guidance for Conducting Civil Works Planning Studies, December 1990. ER 1105-2-100. U.S. Army Corps of Engineers, Washington, DC.

Project Operations - Partners and Support (Work Management Policies), December 1996. ER 1130-2-500. U.S. Army Corps of Engineers, Washington, DC.

The following two IWR Research Reports provide a more in-depth discussion of risk and uncertainty analysis applied to water resources planning:

Guidelines for Risk and Uncertainty Analysis in Water Resources Planning, Volume I Principles. March 1992. IWR Report 92-R-1. U.S. Army Corps of Engineers, Institute for Water Resources, Alexandria, VA.

Guidelines for Risk and Uncertainty Analysis in Water Resources Planning, Volume II Examples. March 1992. IWR Report 92-R-2. U.S. Army Corps of Engineers, Institute for Water Resources, Alexandria, VA.

APPLICATIONS

Of the four models developed to date, two (Hydropower REPAIR and Life Cycle Lock Repair Models) were developed in a research environment, and two (Hoover Dike and Gulf Intracoastal Waterway Models) were developed in association with Corps Districts for application in specific studies. The Hydropower REPAIR model has subsequently been applied for various rehabilitation studies, while the Life Cycle Lock Repair Model remains, as of summer 1998, a research model, not yet applied in a 'real-world' situation.

Hydropower REPAIR

The Hydropower REPAIR model was developed to assist in the general problem of major rehabilitation of hydropower facilities, common across many Corps installations. The general problem involves evaluating the trade-off between continual repair of hydropower unit components (generally turbines and generators) as they degrade over time, or incurring larger, one-time costs to upgrade the components through rehabilitation, typically both improving reliability and increasing output. The model is run as a life cycle model, typically for a 50-year time span.

The existing Hydropower REPAIR model has its roots in a spreadsheet model developed by IWR to assist the Savannah District in evaluating major rehabilitation proposals for Hartwell Dam hydropower. The spreadsheet provided risk-based economic analysis, but model runs required hours to run and changing model parameters was difficult. The Hydropower REPAIR model was developed and subsequently used to help evaluate major rehabilitation proposals at Richard B. Russell, J. Strom Thurmond, Robert S. Kerr and Garrison hydropower projects.

Levee Repair Model

The Levee Repair Model was developed specifically for, and has been applied as part of, the Herbert Hoover Dike Major Rehabilitation Study carried out by the Jacksonville District. This major study was designed to investigate improvements to portions of the levee surrounding Lake Okeechobee. The levee is subject to hydraulic failures through breaching under conditions of high lake levels. Geotechnical studies provided estimates of probability of unsatisfactory performance (PUP) for portions of the levee as a function of lake level. Hydrologic studies were used to develop synthetic lake stage and hurricane surge generators within the Hoover Dike model. Curves representing monetary damages associated with crop loss and non-monetary factors such as population exposure in tributary areas during a breach were developed. The Hoover Dike model provided a framework for formalizing and combining the data inputs from the three disciplines (geotechnical, hydrology, and economics) involved in the study, to provide statistical estimates of economic damages under baseline and rehabilitation alternatives for a 50-year (4 seasons per year) project life cycle.

As of the summer of 1998, the model is being applied directly by Jacksonville District personnel to determine which alternative rehabilitation plans for the initially-studied portion of Hoover Dike will be recommended, and it is intended to use the model for subsequent studies of other portions of the dike.

Waterway System Simulation

The Waterway System Simulation Model was developed as a flexible, relatively general model, in the specific context of a study of structural and non-structural modifications to the High Island to Brazos River reach of the Gulf Intra-Coastal Waterway (GIWW). The High Island to Brazos River study is one of a series of studies of portions of the waterway being carried out by the Galveston District, and a general modeling framework that would be applicable to subsequent studies was desired. The problem involves estimating transportation cost savings benefits associated with improvements to selected portions of the overall waterway system. Benefits are estimated based on reduction in transit time by tows using the waterway.

The model was applied directly to the High Island/Brazos River portion of the GIWW, for a base condition and twelve alternative sets of improvements to the waterway. Model results showed that many of the desired improvements were economically justified.

Life Cycle Lock Repair

The Life Cycle Lock Repair Model was developed to deal with major rehabilitation at an individual lock. It allows user specification of components that make up a lock chamber, and failure modes and failure probabilities for these components. The overall performance of the lock (in terms of service time and downtime) is a function of the state of the individual components of the lock. The model allows for analysis of investments in the individual components (improving reliability), and determines the overall effect on total service time for tows passing through. The model has been developed with test data, and has not, as of this time, been applied in a Corps study.

INFORMATION DISSEMINATION/TECHNOLOGY TRANSFER

The tools and expertise developed at IWR have been made available within the Corps in a number of ways. IWR staff routinely provides advice and consulting to other Corps organizations on the use of the models and risk analysis techniques. Documentation and reports have been generated for the Hydropower, Levee, and Waterway models, and provided to users, cooperating Districts, and other interested parties. Software for the Hydropower model has been made available for download through IWR, and the other models are available upon request. The models are used as tutorials and examples in risk analysis training within the Corps. In addition, papers and presentations on the subject have been delivered at various conferences outside the Corps. Throughout model development, every effort has been made to make potential users aware of the types of capabilities that are embodied in the IWR-developed risk analysis tools, and to encourage their use where appropriate.

A major vehicle for information dissemination is expected to be through maintenance of an IWR-hosted Internet site, containing general information about risk analysis and the technologies developed by IWR. Due to the complexities of the issues involved, and to insure that the models are appropriately applied, direct downloads of the models themselves are not intended to be supported at this time. Rather, site users will be able to post inquiries and requests for additional information, for response by knowledgeable IWR staff.

IWR expects to continue encouraging the use and development of risk-based economic analysis tools, and will be available to provide the needed support and expertise to see that they are used appropriately.

II. BASIC CONCEPTS

All of the models incorporate a common approach to planning. Each model is designed to assist in a documented, repeatable, understandable method of evaluation of plans.

Modeling of complex systems cannot be simplified too far without making the models inappropriate for decision-making. Thus, the models developed require a certain level of knowledge of both the general approaches being utilized, and the specifics of the particular model.

All of the models use a similar construction, and are based on common concepts that are applicable to risk-based economic analysis. Each model, however, has a specific structure designed around the class of problems for which it was developed.

The conceptual underpinnings that are common to all the models are described below. The unique structure of each model is described in later sections of this report.

PLANNING APPROACH

All models support a planning approach designed to provide decision-makers with information about the economic impacts of implementing choices that affect the reliability and/or performance of the physical system under study. Through user specification of a ‘base case’ representing the existing situation (without project) and as many alternatives as are desired, the consequences of a wide range of options can be explored. By providing a tool that allows for rapid assessment of the consequences of an alternative, a much broader range of possibilities can be included in the planning analysis.

All models have in common:

- A simulation-oriented approach in which an abstraction of the physical/economic system is modeled in the computer;

- Evaluation and comparison of economic impacts of existing (without project) and alternative (with project) conditions;

- Inclusion of, and accounting for, all costs and benefits that are affected by the investment decision under study, discounted to present value. Costs are typically repair costs, operation and maintenance costs, direct cost of project improvements, and opportunity costs (value of lost outputs). Benefits are typically taken as reductions in costs (e.g. costs associated with travel time of tows, or with agricultural damages due to flooding);

- Incorporation of uncertainty for selected variables whose uncertainty can be estimated, and where the variable plays a part in determining benefits/costs affected by investment decisions;

- Generalization of the models to allow as much specification of model behavior for a specific situation as possible to be set by the user as input data (rather than being incorporated directly into the model, and thus unchangeable by the user);

- Output of sufficient detailed information as to how the models operate internally to insure that the simulation is behaving reasonably.

RISK-BASED ANALYSIS

In order to determine the advisability of investment decisions, some predictive method is generally required. That is, we need to be able to predict the impact of the investment on the outputs of the system under examination to determine if the investment is in fact worthwhile.

Risk-based analysis is founded on the understanding that we generally do not have sufficient information to describe complex systems deterministically. That is, we cannot predict precisely what output a system will yield given a certain set of inputs. This uncertainty in the outputs comes from two primary sources:

- Lack of knowledge of how the system really is organized, what inputs are important, and how portions of the system interact;

- Lack of knowledge of the exact values of inputs to the system;

Risk-based approaches attempt to deal with uncertainty in predictive analysis in an explicit manner, clearly defining the model of the phenomenon that is being utilized, identifying inputs, and quantifying their variability. Variability is usually defined by specifying a statistical distribution of inputs, rather than a single value.

Risk-based analyses provide more than a single point prediction of the output associated with a set of inputs; rather, typical risk analysis yields a statistical distribution of outputs, based on an assumed statistical distribution of inputs. The task of risk-based analysis is to combine the variability of the inputs, based on knowledge of how the system operates, to obtain estimates of the variability of outputs. For complex systems with many sources of variability, this is not a simple task.

In the past 30 years, risk-based analysis has increasingly been seen as the appropriate methodology for technical evaluations, ranging from structural engineering applications to assessments of population exposure to carcinogens. Risk analysis is recognized as good engineering practice. As well, it is mandated for many investigations carried out within the Corps of Engineers.

ELEMENTS OF UNCERTAINTY

System Structure

As noted above, a great deal of inherent uncertainty is based on lack of knowledge of how a system operates. While this can never be eliminated, an approach that specifies what portions of the system are to be modeled, and how that model operates, at least allows for discussion, examination, and modification of the important elements and processes of the system. Thus, construction of a model makes explicit all behaviors and assumptions. Once a model has been constructed, it can be tested and modified, until it satisfactorily reproduces historical and/or reasonable behaviors. It is important for the model construction to be an 'open process', with the internal behaviors of the model proposed, described, and negotiated, rather than simply presenting the model as a 'black box'.

All modeling of physical systems involves abstraction, that is, simplification of the real world problem to a level at which it can be handled analytically. A good model has a reasonable level of abstraction, such that the internal components map adequately to things for which data can be obtained. Too detailed a model means that too much, or unobtainable data, are required to run the model. Too gross or abstract a model means that important behaviors cannot be captured. The art of modeling lies in developing an appropriate level of abstraction for the particular problem at hand.

In addition, an appropriate boundary for the problem must be defined. It is not possible to incorporate all external influences within the model, or to model all sources of variability. Some things must be set as fixed boundary conditions, not altered within the model. The boundary of the model depends on the particular arena being investigated. Thus, when the focus of a hydropower model is on rehabilitation of individual components at a power plant, it is probably not worthwhile to include within the boundary the entire power grid, and all other plants in that grid, to which the plant in question provides power. Alternatively, if macro-economic issues and broad scale investment decisions and policies are to be investigated, a more comprehensive system-level model might be appropriate – but such a model could not have the same level of detail about each individual generating facility.

Physical System Performance

Engineering systems are typically envisioned as being composed of discrete elements with certain defined behaviors, which inter-relate in some fashion. It is not usually possible to develop consistent closed-form solutions describing the behavior of the system as a whole; rather, the system behavior is developed out of the behavior of the individual elements, and the manner in which they inter-relate.

It is frequently worthwhile to view a physical system as a hierarchy of individual components. Thus, a power generating facility can be conceived as a combination of generating units, each of which, in turn, is made up of a turbine component and a generator component. A lock is composed of one or two lock chambers. Each lock chamber has components such as gates, valves, pumps, and control systems.

Due to interactions between the elements of the system, the output of the system as a whole is something other than the sum of outputs of elements at the lowest levels. It is not meaningful to speak of the power output of a turbine in the absence of a generator. The service time of a lock is dependent upon the rate at which the chambers fill, the rate at which the gates open and close, etc.

While these hierarchical views are not the only methods of organizing and inter-relating discrete elements of a system, they are often convenient abstractions for the purposes of modeling. Once the inter-relationships are defined, efforts can be focused on defining the behavior of the individual system elements.

Each individual element can be viewed as being in a particular state at a given time, with the state determining how that element contributes to the output of the system (or to the behavior of the next level up in the hierarchy). At the simplest level, an element can be in one of two states: operational or non-operational (failed). The transition from operational to non-operational is viewed, in risk-based analysis, as a probabilistic process. Over time (or due to external circumstances such as a collision of a tow with a lock wall), a particular element of the system can degrade and become less fit for its intended purpose. It is not generally possible to state, for example, that when a turbine reaches 20 years of age, it will definitely fail, and it will always be in good operating condition prior to 20 years old. Some turbines may fail at an early stage, while others perform adequately for much longer periods.

Historical information can provide curves called hazard functions that give probabilities of failure as the element ages. Within the Corps of Engineers, the generally-preferred term to refer to such probability curves is *Probability of Unsatisfactory Performance (PUP)* (Figure II-1). This terminology recognizes that a particular component may not fail (in an engineering sense), but may become unfit for its intended purpose, and thus in need of repair.

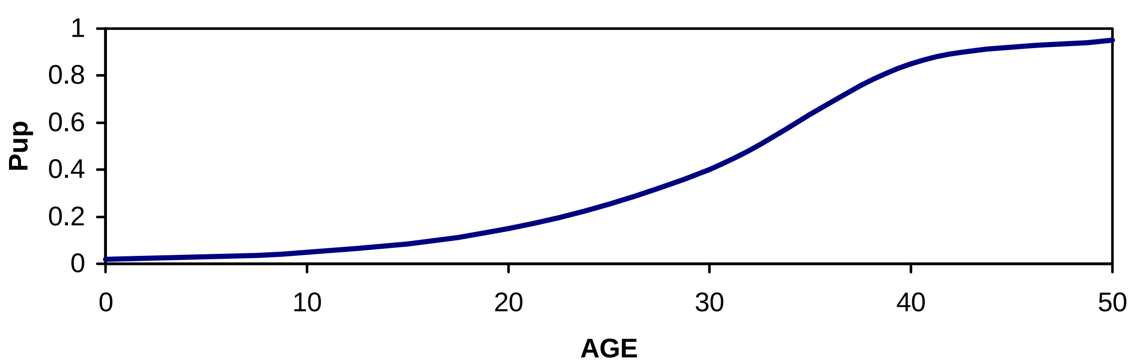

Figure II-1. PUP Function

PUP functions give the probability (from 0 to 1) that a given component will become unsuitable for use, based on some independent variable, such as age, or lake stage, or number of lock cycles. If the independent variable is known during the course of the model simulation, then the PUP function gives the probability that the component will fail at that level of the independent variable. This is generally tested within the model by generating a random number between 0 and 1, and comparing that number to the value of the PUP function. Thus, if at age 23 years, the value of the PUP function for a turbine is 0.3, generation of a random number less than 0.3 indicates a failure of the turbine, while generation of a number more than 0.3 means the turbine continues to operate. As the simulation proceeds in time, the turbine ages, and the value of PUP increases, meaning greater likelihood that the next time a random number is generated, it will be smaller than the PUP, and consequently indicate unsatisfactory performance. The PUP function is taken as deterministic – uncertainties within the PUP functions themselves can best be handled by use of sensitivity analysis, i.e. running the models with different sets of PUP functions, embodying different assumptions about unsatisfactory performance (e.g. optimistic, pessimistic, most likely).

Table II-1. Simulation Results Based on PUP Function

Cycle (age)	PUP	Random Number	Failure
5	.1	.555	No
6	.2	.323	No
7	.3	.219	Yes
8	.4	.666	No

The above formulation provides only a single failure mode, that is, the component can only be operational or non-operational. This is frequently limiting from a modeling point of view, in that it is recognized that components are likely to be in one of a number of possible states, not simply operational or non-operational. A component can be in excellent condition, good or average condition, poor condition, or unusable, or any other set of defined states describing the component, with associated differences in behavior and contribution to overall system output. A more general formulation allows for multiple failure modes, that is, allowing a transition from a current state to more than one other state. As an example, a collision of a tow with a guidewall at a lock could be either serious or minor. A serious collision would result in a poor condition of the guidewall, with attendant requirements for repair, while a minor collision might result in small damage with no perceptible effect, or some state in between. Models can be formulated using continuous descriptors of a state (such as a condition index from 0 to 100, with any allowable value in between), or with certain allowable discrete states.

When a set of states are defined for a component, it can transition between those states – degrading due to natural phenomenon or accident, or improving based on repair, maintenance, or rehabilitation. Just as the PUP function defines the transition between operational and non-operational, incorporation of multiple states within a model framework requires the definition of state-to-state transition probabilities, which could be variable based on age or some other independent variable. Thus, the introduction of multiple states (discrete or continuous) allows a model to better portray certain situations, but at the cost of additional data requirements, which may be significant.

Of the models developed to date, the Life Cycle Lock Repair model makes the most extensive use of multiple states and failure modes, while the Hydropower REPAIR model allows only for operational/non-operational states. The Levee Repair model provides for three states of a component: intact, low velocity breach, or high velocity breach. The Waterway System Simulation model does not examine component reliability, thus it does not use the concepts of component failure, PUP's, or state transitions.

Economic Impacts

It is certainly recognized that costs of rehabilitation investments and repairs, and benefits associated with outputs are properly treated as probabilistic variables, just as are the physical variables of the system. While there is no reason why such elements of uncertainty could not be included in the models, economic impacts have been treated as deterministic factors associated with the physical system in the models developed to date.

ENGINEERING-ECONOMIC ANALYSIS

Analysis Approach

The approach to engineering - economic analysis used within the models is based on National Economic Development benefits, as enunciated in the Principles and Guidelines (U.S. Water Resources Council, "Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies", 1983), and various Corps-published planning guidelines. Under this approach, as complete as possible an enumeration of costs and benefits of the existing situation (without-project, or base condition), and alternative projects (with-project) is carried out. Net benefits, taken as the difference between the discounted benefits and the discounted costs, are calculated. The change in net benefits between the base condition and an alternative, as compared to the cost of implementing that alternative, yields a benefit-cost (B/C) ratio, which can be used to provide comparable assessment between various alternatives.

The purpose of the models is to translate changes (investments) in the physical system into changes in economic costs and benefits of the system, making the connection between the engineering behavior of the system and the economic behavior of the system. While the analysis is carried out primarily on an economic basis, additional outputs of the various models can be used for further decision support.

Present Value

Costs and benefits are realized at different times during a project life. It is important to delineate the stream of benefits and costs as they occur over time, and use a standard method of present-valuing based on interest rates to obtain comparable measures, such as net present value, or average annual benefits and costs, that can be used to compare alternatives with different cost and benefit streams.

Elements of Costs/Benefits

Cost elements include:

- Investment Costs of project alternatives - cost of the rehabilitation that is done at the beginning of the period to improve reliability, reduce the likelihood of unsatisfactory performance in the future, and possibly increase capacity and/or output;

- Operation and maintenance costs – includes all labor, material and supplies required to maintain the project in full working order under normal operating conditions; these costs may be reduced over the base case when investment is made in rehabilitation;

- Emergency Repair Costs – incurred to repair a project element that is operating unsatisfactorily;

Benefits include:

- Direct benefits are the outputs generated by the project under evaluation. For example, the benefits of a hydropower project are the power and energy produced by the hydropower units.

- Reduction in user costs as compared to the without-project case (e.g. reduction in travel costs associated with improved transit times through a lock or waterway system)

Not all costs and benefits are included in each analysis; in some cases, benefits are measured primarily as reduction in costs, rather than as direct benefits. In some cases, opportunity costs may be relevant to the analysis, while in others they may not be present. The key feature of all models is the ability to compare the base condition to all alternatives. A proposal is considered acceptable if the net benefits produced by the proposal are greater than the base condition. One proposal is considered superior to another if the net benefits are greater. The models can calculate the benefits and costs for a range of proposals against the base condition and each other.

Analysis of Investment Decisions

The advisability of an investment decision is based on the economic benefits of incurring investment costs at various times in the project life, to improve project outputs and reduce costs later in the project life. A variety of possibilities can be explored, including:

- Making large investment costs in major rehabilitation early in the project.
- Making smaller investments (such as for maintenance) at periodic times during the project life.

Both the timing and magnitude of investments can (and should) be investigated.

Improvement in project outputs can come from:

- Reduction in outages or delays associated with failures (and associated economic losses);
- Reduction of costs associated with non-routine, costly emergency repairs;
- Increase in project outputs associated with greater capacity;

LIFE CYCLE MODELING

Life cycle modeling is an approach to engineering-economic analysis that evaluates all costs and benefits over the useful life of a project, accounting for time-based changes in the physical system. As a system ages, its performance can be expected to degrade, requiring increased repair and maintenance costs, and reducing outputs. A rehabilitation investment made today will likely reduce future degradations seen in Figure II-2. Given the time cost of money, reduction of uncertain future costs with certain dollars spent in the near term may or may not be justified. Life cycle modeling looks at the entire stream of costs and benefits over the anticipated useful life of the project, under without project (base case) and alternative with-project conditions. Results are usually expressed as net present costs and net present benefits of project operation over the entire life cycle.

In the accompanying illustration, an initial investment in year 4 associated with the rehabilitation alternative reduces repair costs in the outyears, as compared to the base case. Whether or not this is justified depends upon the discount rate, and the precise stream of costs between the two cases.

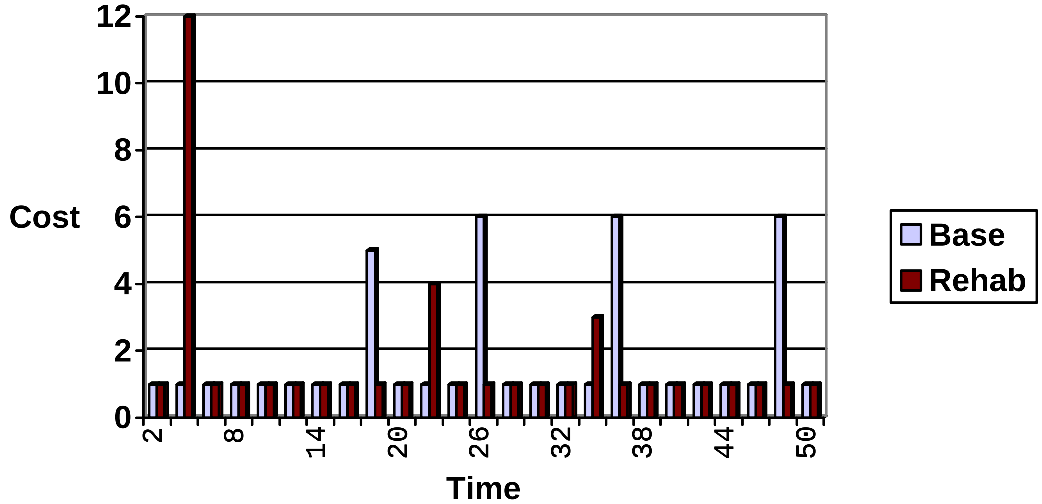

Figure II-2. Life Cycle Costs

Life cycle modeling implies the passing of time. As such, time-based changes pertinent to the system being examined must be captured within the model. Growth in demand, in particular, is important. It cannot be assumed, for example, that the number of tows using a waterway, or the mix of tow types and trips, will remain constant over 50 years. Life cycle modeling thus may require additional data, and a more complex model. At the very least, life cycle modeling requires the user to be explicit about what elements of time-based change are included in the model, and what are not.

MONTE CARLO SIMULATION

The complexities of the combined engineering-economic problem of risk-based analysis, in which there are uncertainties associated with the physical performance of systems, and the economic consequences of that performance, are typically addressed through the use of Monte Carlo simulation techniques. The complexity of the underlying problem usually dictates that there is no closed-form, analytical solution. Instead, computer-based simulation is used to provide numerical characterization of the behavior of various alternatives. Monte Carlo simulation is particularly useful for physically-based real-world problems, where the results of the simulation can be tested against historical and reasonable behaviors.

Monte Carlo simulation combines uncertainties in many variables that describe a system, to obtain a statistical description of the behavior of the system as a whole. This is accomplished through repeated runs of a simulation model, varying the input data based on the statistical descriptions of uncertain parameters.

The important sources of uncertainty for a given problem (failure rates, for example) are identified, and described statistically. This data is then used within a simulation model developed for the problem. At each point within the simulation at which descriptive data for uncertain variables are required, the statistical distribution is used to select a value (through random sampling from the distribution), which will thus differ from simulation run to simulation run. Many simulation runs are made, and the resultant overall statistics are used in the decision-making process. A large amount of data must be managed, and the simulation must provide sufficient information to allow for validation and verification.

Critical issues for effective use of Monte Carlo simulation are: appropriate abstraction and definition of the problem; efficiency of computation, to allow for multiple iterations and associated statistical validity; management of input data and ease of use; and analysis, verification, and visualization of results.

OBJECT ORIENTATION

All of the models developed make use of an object-oriented approach. Under this approach, the model is constructed as a set of interacting objects. Each object has internal data and a certain set of capabilities, and responds to requests with certain behaviors. An object can be thought of as something that 'knows' some things and knows how to do some things. For example, in a waterway model, a tow object can 'know' how fast it can proceed in certain portions of the waterway, and what its operating cost is. It can provide information on where it is in the waterway back to the overall model.

A model is built by defining what objects are involved, what each object knows, what it can do, and how it relates to the other objects of the model. For the case of a Monte Carlo simulation, where real world, physically-based systems are being modeled, the approach is particularly valuable. It becomes possible to map clearly between the system being examined and the model implementation, because the model objects become analogs of the real-world components of the system.

The object-oriented approach is supported by many modern computer-programming languages, and has achieved great popularity in recent years, due to the advantages it provides. In particular, computer programs are easier to design, develop, maintain, and improve. Programs are often constructed out of re-usable parts (such as a random number generator object), which can be applied in a number of different programs.

DATA-DRIVEN MODELS

An important design choice was made to develop general, rather than site-specific models. Each model is constructed such that it deals with a general problem within a problem domain (lock modeling, hydropower, waterway system, levee failure), attempting to capture the important processes and elements of that problem. The general character of the behavior of the system is defined within the model, but the particular data on which the model operates is read in as model input. This approach is referred to as data-driven modeling. Even when a specific District problem was being investigated, as for the waterway system and levee failure models, every attempt was made to generalize the structure of the problem, to allow the model to be readily used and adapted elsewhere, or for further studies of the same type.

The data-driven approach places greater demands on the user for development of input data, but provides advantages in terms of flexibility, ease of use, and ability to use the model across a range of studies. Obviously, there is a trade-off between making the model too general, thus placing too great a demand on the user to specify all behaviors as input data, and making it too specific, confining and limiting the utility of the model. There is no hard and fast rule to determine where the line should be drawn, but, in the present case, the tendency was to choose greater generality wherever possible.

An important consideration in all modeling, but particularly in data-driven approaches where the role of input data in characterizing the problem is highlighted, is that the data be obtainable in the real world. That is, the level of abstraction of the model should be such that the input data that drives the model is both meaningful and obtainable through measurements or estimates based on engineering judgment in the real world.

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III. MODEL DEVELOPMENT

TECHNOLOGY CHOICES

Development of the models required a number of design decisions and technology choices. Chief among these was the decision between writing custom computer code, or using a general simulation package, such as Stella or Simscript.

Custom Programming vs. General Simulation Package

General simulation packages are designed to solve broad classes of problems, such as discrete event or continuous simulations, within a particular framework. A large number of such packages are available, with varying capabilities, orientations, strengths, and weaknesses.

Custom programming involves use of a programming language, such as C++, Java, Fortran, or Visual Basic. It is likely to require more initial effort, and is less easily modified, but provides the capability to specify the problem exactly as desired. Custom programming approaches typically have computational speed advantages over general simulation packages.

General simulation packages are almost entirely data-driven, placing the burden on the user for specifying almost the entire behavior of the system. There is a learning curve associated with using the particular package, as well as purchase or licensing costs. The problem structure and definition is constrained by the specific capabilities of the general simulation package. In addition, there are typically processing speed advantages in using custom programming approaches.

Custom programming was selected as the desired approach, for three primary reasons:

- Ability to define and specify the problem as desired;
- Speed of processing, allowing for running life cycle models with large numbers of iterations;
- Ease and cost of distribution of the finished product;

Programming Language

As noted previously, there are distinct advantages to using an object-oriented approach to the problem. At the time of project initiation, the C++ language was the primary vehicle for object-oriented programming. Initial implementation was done using the Borland C++ compiler, but later versions were implemented in Microsoft Visual C++ (Version 5.0), which became the market leader. Since the beginning of the project, other languages have included object orientation, notably Visual Basic and Java, but C++ remains the general choice for programs that must run quickly.

Platform

Initial programming efforts and proof-of-concept prototypes were carried out using simple, file-oriented input/output, and were relatively platform independent. As it became clear that more complex user interfaces and data base structures to support the required model input data were required, choices were made that oriented model developments towards desktop computers running Windows (Wintel standard). With the introduction of Windows 95, all model efforts were converted to a 32-bit environment, capable of being run on Windows 95, 98, and NT platforms. Development was carried out in a Windows 95 environment.

Model Architecture and Implementation Framework

A common architecture was used in developing all models. This architecture as seen in Figure III-1 has proven to be very powerful and flexible. User information and problem specification is localized in a *database* (specifically Microsoft Access). Computation is carried out by the *simulation kernel*, programmed in C++. The kernel reads information from the database, carries out the needed calculations, and stores summary results back into the database (as well as generating additional, supplementary files used for detailed analysis). A *user interface* serves as the simulation front-end. The user interface incorporates menus and forms that structure the input, editing, and visualization of the required data. A *reporting/graphics module*, integrated with the user interface, allows for generation of a variety of reports and

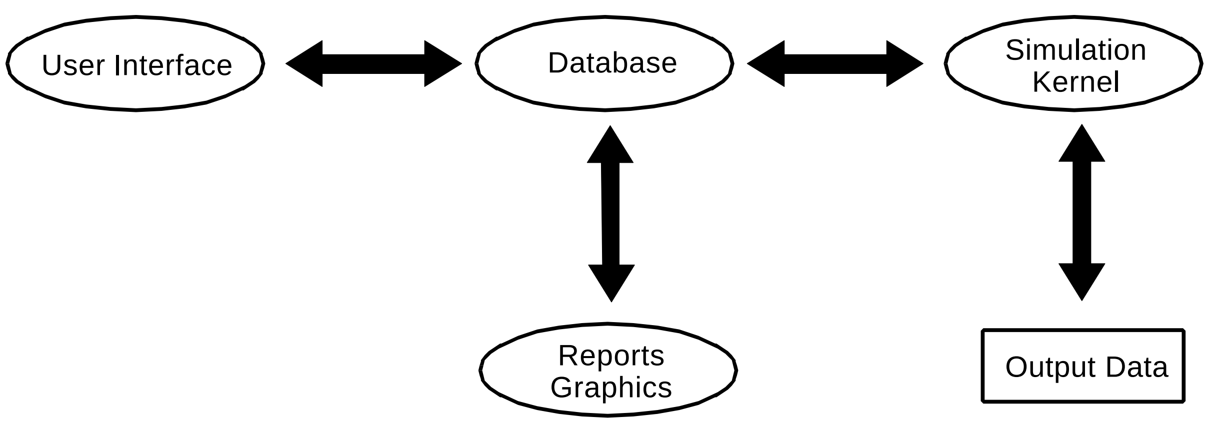

Figure III-1. Model Architecture

graphical representations of the results. The user interface and reporting/graphics module are implemented in Microsoft Access and Visual Basic, and make use of custom controls (third-party utility software for specific purposes, such as displaying graphs on-screen). This architecture lends itself to team software development, maximal use of standard software and re-usable components, and allows the problem-specific nature of each model to be localized.

DEVELOPMENT TECHNIQUES

Software development was carried out through the use of the related software engineering approaches of rapid prototyping and spiral development. Rapid prototyping emphasizes a brief initial problem scoping and design phase, moving quickly to a pilot implementation in a working computer program. Spiral development means that the software is developed as a series of program versions. Each version incorporates additional features, and can be tested by users to insure that the desired behavior (both from a technical and usability standpoint) is obtained. Spiral development assumes that there will be many program versions, and close interaction and communication between software developers and users.

These techniques are in contrast to a much more structured and formal approach, using detailed design specifications, and perhaps one or two program versions. Experience at IWR has shown that rapid prototyping and spiral development are much more effective, serving quickly to identify the complexities, problem areas, and data requirements associated with the problem. The approach does, however, require much more involvement on the part of the software users on a continuous basis throughout the development cycle, and willingness of the software developers to work more interactively, making many changes and adjustments in response to user concerns and testing.

EVENT-BASED VS. PERIOD-BASED MODELS

The simulation models developed fall into two basic categories: event-based, and period-based (or cycle-based) models. A period-based model divides up time into discrete periods of known length (years, months, weeks) as seen in Figure III-2. All the calculations are made for a given period, and then time is advanced to the next period, for the duration of the simulation. The simulation is in a known state during each period, i.e. all of the variables of the simulation have a defined value, assumed to be constant for the period. In an event-based model, a set of events that the model is concerned with are defined, and time moves forward in jumps, as each event takes place. The simulation state (value of the simulation variables) is known as of the time of each event. Every event of interest is handled individually. Under the period-based formulation, time moves forward in constant increments, and behavior within a time increment is not considered. If multiple events take place within a time increment, all that can be done is to count and 'lump' them in some fashion, rather than handling them individually.

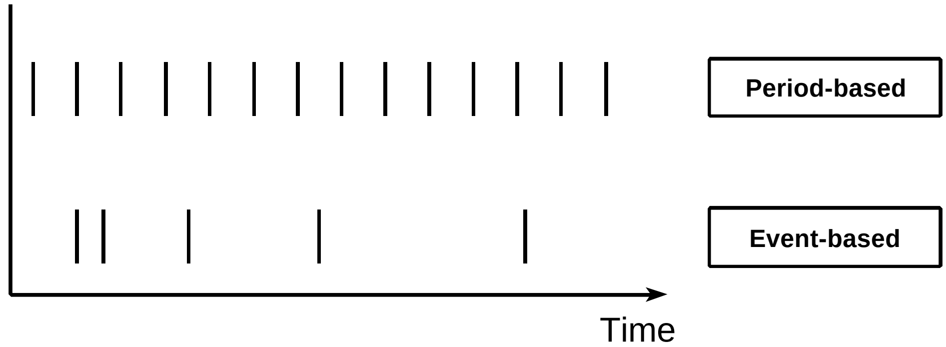

Figure III-2. Period vs. Event

In general, model formulation and calculations are simpler for the period-based model than the event-based model, but assumptions required in the period-based model about averaging of data may be limiting. As an example, the Hoover Dike model is period-based, using four quarters in a year. Probabilities are associated with the occurrence of a hurricane in each quarter. The periodic structure of the model allows for only one hurricane per period. Thus, a maximum of four hurricanes can take place within a year.

The choice of period-based vs. event-based is problem- and usage-specific. Both types of approaches have their advantages and disadvantages.

The Hydropower REPAIR model is a yearly periodic model, and the Levee Repair model is a quarterly periodic model. The Life Cycle Lock Repair and Waterway System Simulation models are both event-based.

IV. MODEL DESCRIPTIONS

The initial impetus for model development was for support of risk-based analysis of major rehabilitation proposals within the Corps, through development of a consistent, easy-to-use set of software tools that would implement the techniques required in Corps guidelines. Most of the studies done were quite situation-specific, generally through use of custom spreadsheets that were difficult to construct and modify, and slow in computation.

The majority of rehabilitation studies being proposed at the time were for hydropower facilities and navigation improvements. Work was initially oriented towards development of a general-purpose model that would serve for any type of rehabilitation study, but it soon became clear that the particular nature of each problem required different levels of abstraction, conceptual bases, and modeling approaches. Accordingly, work on the general problem for hydropower proceeded independently, followed in May of 1994 by efforts on the navigation problem.

As others became aware of the capabilities of IWR in the risk-based modeling arena, requests for assistance from Corps districts led to the development of the Hoover Dike and GIWW models. In each case, many of the capabilities and concepts of each model were drawn from the prior modeling efforts, but problem-specific aspects dictated the need for separate models. Each model was constructed to be as general-purpose as possible, consistent with the needs of the particular problem under study. Thus, in each case, the specific problem was generalized, and the general problem then abstracted, with the model attempting to simulate the abstraction of the general problem. The following table summarizes the status of each of the models developed to date.

Table IV-1. Tools for Risk-Based Economic Analysis

Model	Purpose	Type	Developed For	Adaptability
Hydropower REPAIR	Rehabilitation Investments for Hydropower Plants	Period-based, Life Cycle, single failure mode	IWR	General Purpose
Life Cycle Lock Repair	Rehabilitation Investments for Navigation Locks	Discrete-event, Life Cycle, multiple failure modes	IWR	General Purpose
Levee Repair	Rehabilitation Investments for Hoover Dike, FL	Period-based, Life Cycle, two failure modes	Jacksonville District, USACE	Some modifications likely required for other situations
Waterway System Simulation	Navigation Improvements on Gulf Intracoastal Waterway	Discrete event, waterway system simulation	Galveston District, USACE	Enhancements for broader use are in progress

Descriptions of each of the models are presented below. For each model, the general nature of the problem addressed by the model is described, as is the manner in which the problem is generalized and abstracted in the model. The overall model structure, concept, and limitations are presented. The purpose of these descriptions is to present the general nature of the effort, rather than detailed examinations of the internal workings of the models, which are relatively complex.

HYDROPOWER REPAIR MODEL

Model Structure, Concepts, and Limitations

A hydropower facility consists of a number of different components that contribute to the total facility output. Typically, these components are turbines and generators, which combine to form a generating unit. Multiple generating units make up a facility. Other components may be present as well, such as switchyards.

Over time, these elements may degrade in performance, with lost efficiency. At any time, a catastrophic failure is possible as well (complete loss of capability). These are uncertain events, and must be analyzed in a risk-based framework. Repairs can be made on an as-needed basis, with associated costs and down-time, or major rehabilitation can be scheduled to provide improved performance, increased capacity, and the likelihood of lesser degradation over time. The economic investment decision requires determining whether a major rehabilitation investment is justified (with a certain cost), as compared to the unknown, probabilistic costs associated with repair as failures take place.

Rather than modeling the specific behaviors of turbines, generators, and switchyards, the problem is abstracted based on a hierarchical structure, in which a hydropower facility is composed of units, which are themselves composed of components as seen in Figure IV-1. Components are the elements that fail, and incur costs of rehabilitation or repair.

The lowest level element in the tree is the component (typically a turbine or generator). A component is something that can degrade over time, fail, and be repaired. Components are combined into units, which then combine at the facility level (e.g., the power plant). Units are operational only if all components of the unit are operational (i.e., both the turbine and generator must be operating for a unit within the power plant to be on line). Units, if operational, may generate some output. Units can be combined into groups, with the output of the group dependent upon the operational status of units designated to be critical within the group. That is, if a critical unit is not operational, then there is no output available from any of the units within the group (even though other units in the group are themselves operational). This capability is designed to allow for modeling representation of situations where a single switchyard handles the output from a number of generating units.

Benefits accrue at the facility level, based on the operating status of all of the units. Hydropower facilities generate output into an electrical grid. The value of that output, in the real

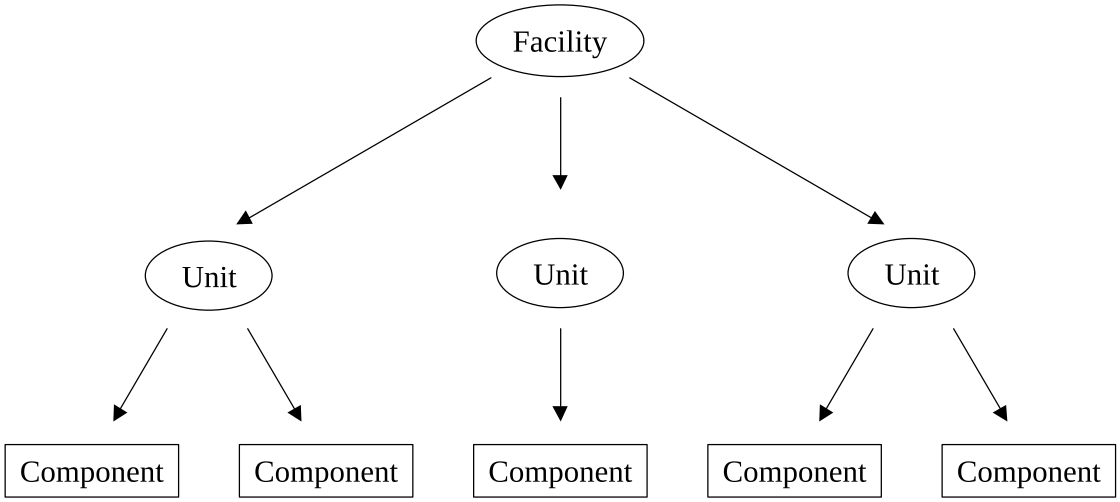

Figure IV-1. Hydropower Facility Architecture

world, is dependent upon a number of factors, including the value of alternative sources of power, the quantity of the power output from the facility, and the reliable capacity of the facility. The issue is economically complex. For the purposes of the model, the simplification is made that external factors (demand, behavior of other facilities on the grid, contracts, etc.) remain constant. Thus, benefits associated with the facility can be determined solely by the current operating characteristics of the facility itself, and external constants describing the way in which the output to the grid is translated to economic benefits. The boundary of the model, then, is drawn around the facility, at the point at which the facility provides output to the electrical grid.

As noted above, components degrade over time. In a hydropower facility, the basic driving force for degradation is simply aging of components (as opposed to other types of facilities, such as locks, where cycling of the gates, or collisions with tows, contribute to degradation of components). In the real world, degradation can be gradual, leading to lost efficiency, and repairs can be incremental. This implies different operating levels or states of a component, and transitions between those states, based on probabilistic failures, and repairs. The complexities of implementing this multi-state component approach, in particular in terms of both obtaining and managing the data defining the state transition probabilities, led to a simplification in the model. In the Hydropower REPAIR Model, each component is allowed to exist in only two states: operational, and non-operational, that is, there is only a single *failure mode* allowed for each component. Similarly, no provision is made for levels of operation of a unit. It is either functional or non-functional.

The model is period-based, using a yearly period, and typically running 50-year life cycle simulations.

Risk-based behavior is incorporated primarily through specification of PUP functions for components, giving the probability of unsatisfactory performance of a component based on an effective age of the component. Effective age is used as a surrogate for the combination of chronological age and condition of the component. Thus, for each component, a curve is specified, giving the UP probability at a given effective age. By setting an initial effective age for a component, the user is defining the initial probability of unsatisfactory performance, in the first period of analysis. As the simulation progresses, the effective age of each component increases, and the probability of unsatisfactory performance (and thus downtime, repair costs, and reduced facility output) increases.

A rehabilitation, which is directed at the component, occurs at a designated period, placing the component on a new PUP curve, with lower probabilities of unsatisfactory performance, for the duration of the simulation as seen in Figure IV-2.

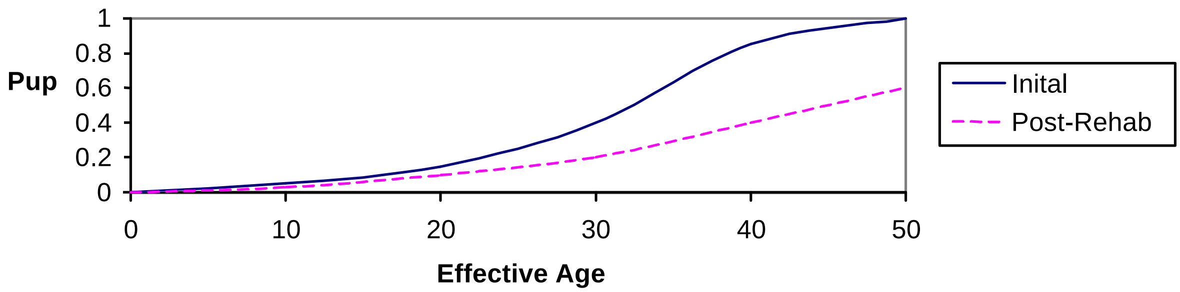

Figure IV-2. Post Rehabilitation Performance

Model Inputs

The user specifies the hierarchy of units and components within the facility.

For each component, an initial effective age and initial PUP function are assigned. PUP functions are defined as piece-wise linear functions. The cost of repair and duration of downtime associated with repair of the component are also specified.

For any rehabilitation alternative, the period at which the rehabilitation takes place, the component(s) rehabbed at that period, and the new effective age and PUP functions associated with the post-rehab condition are set.

Economic data, including cost schedules for the rehabilitation alternative, generating capacity of units, and curves and constants allowing for calculation of power benefits are specified.

Model Processing

Each iteration of the simulation is carried out for a designated number of periods (typically 50). Each iteration generates data on component failures, and discounted costs and benefits over the 50-year life cycle. Multiple iterations are run, consistent with Monte Carlo simulation approaches, and statistics are accumulated.

In each iteration, the simulation proceeds, period by period. At each period, each unit of the facility is examined in turn, and each component of the unit is tested for unsatisfactory performance. This test is carried out by generating a random number from 0 to 1, and comparing this to the value of the PUP determined based on the effective age of the component being examined (through lookup into the function). All components are tested, to determine the operating status of the unit in the period. If a component fails during the period, the required downtime time is determined, and the component is held in non-operational state for that period. Repair costs are incurred.

When the state of all components for a unit has been determined for the period, the state of the unit can be tentatively defined (recall that some units are critical units to the operation of other units). When the tentative state of all units has been determined in a period, then the final state of all units can be determined. At this point, the output of the facility can be determined.

As the simulation proceeds, the effective age of components increases, leading to increasing likelihood of unsatisfactory performance. If a rehabilitation alternative is being tested, the component data (effective age, PUP function) are re-set at the time when the rehabilitation for the component becomes effective. At each period, all costs (repair, operation and maintenance, opportunity) are determined, discounted to a common year, and added to a total cost.

Outputs

Hydropower REPAIR contains many reports and graphs that depict the analysis of simulation generated data and data describing the simulation process. Reports include an input data report, simulation comparison reports, and ASCII text files depicting the simulation process. The following inserted report is the Scenario Description Report. It contains all of the input information for a Scenario and Study. Graphics include a diverse range of iteration and cost data. As seen in Figure IV-3, many options exist that enhance the usefulness and analysis of the graphs in the application.

Scenario Description Report

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SCENARIO Scen1		Base condition for all Prospect Major Rehabs			
Study Prospect1		**Rehab Plan**			
Iterations	1000	**Policy Option**	Repair as Needed	**Energy Value**	$0.034
Cycles	35	**Unadjusted Capacity Value**	$93.21		
Interest Rate	7.33%	**Thermal Alternative availability**	97.10%	**Start Year of Analysis**	1997
Random Seed	1701		0.05	**Base Year of Analysis**	1999
		Flexibility Adjustment Factor	0.05	**Base Year of Analysis**	1999

Study Description

Study: **Completed layout for Prospect major rehab** **Prospect1**

Dependable Capacity

STUDY: Prospect1

DESCRIP:

NUM_POINTS: 7

	Installed Capacity(kW)		Dependable Capacity(kWh)
X1:	0	Y1:	0
X2:	38000	Y2:	37000
X3:	76000	Y3:	74000
X4:	114000	Y4:	111000
X5:	152000	Y5:	148000
X6:	163000	Y6:	154000
X7:	179000	Y7:	166000
X8:	0	Y8:	0
X9:	0	Y9:	0
X10:	0	Y10:	0

Current Energy Generated

STUDY: Prospect1

DESCRIP: Function 1

NUM_POINTS: 6

	Operating Capacity(kW)		Energy Generated per Cycle(kWh)
X1:	0	Y1:	0
X2:	37375	Y2:	311772000
X3:	74000	Y3:	400000000
X4:	111000	Y4:	430000000
X5:	149500	Y5:	434511000
X6:	179399	Y6:	459833000
X7:	0	Y7:	0
X8:	0	Y8:	0
X9:	0	Y9:	0
X10:	0	Y10:	0

Page 1 of 5

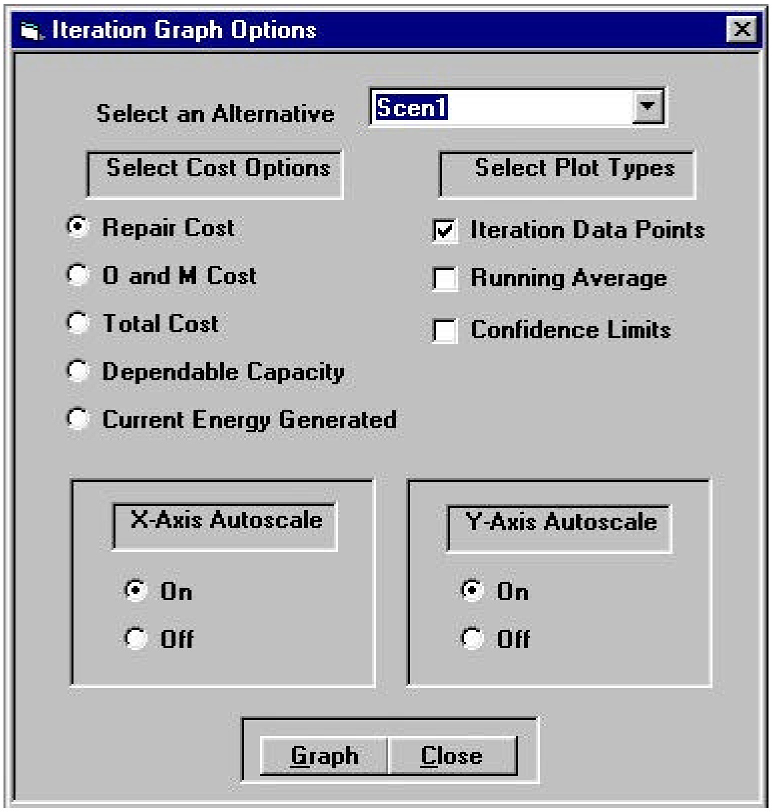

Figure IV-3. Iteration Graph Options

Applications

To date, both the Savannah and Omaha Districts have been successfully applied the Hydropower Repair model to their facilities to evaluate the benefits of expenditures applied to component upgrades.

LIFE CYCLE LOCK REPAIR MODEL

The Life Cycle Lock Repair Model was initiated in May of 1994, after recognition that the structure of the Hydropower REPAIR model would not be suitable for problems involving rehabilitation of locks. Rehabilitation at locks involves improvements to components such as gates, valves, and guidewalls. Locks do not generate direct outputs, as do hydropower plants. Rather, improvements at a lock are intended to reduce the transit time for commercial vessels, through reduction in outages at locks, and faster processing when the lock is in operation. As with the hydropower model, rehabilitation and repair are directed at individual components, and the performance of the individual components will determine the overall performance of the lock.

The problem of evaluating investment at a lock is properly embedded in a larger *systems* model of a complete waterway system. This is because improvements at one portion of the waterway are negated if they only serve to speed vessels to other portions of the waterway, where they encounter additional delays. What is important is a reduction in overall travel time from trip origin to trip destination. In addition, there are economic considerations involving whether or not a particular trip will be initiated, given the option of transporting a commodity by rail, truck, or pipeline, rather than on the waterway. The general problem is quite complex, involving issues of spatial economics and fleet availability. Highly detailed, situation specific models have been developed, but these models are complicated and require extensive parameterization. Moreover, these models do not operate at a level of granularity that allows for assessment of the impact of investments at individual components. Thus, they are not generally suitable for evaluating the advisability of a single investment for a component at a single lock, such as is being explored in major rehabilitation studies.

Accordingly, the navigation lock model takes, as its boundary, a single lock. There is no interaction between the delays incurred at the lock and arrival of commercial vessels at the lock. This is a clear simplification of the real-world situation, but is justified based on the intent of the model.

The key differences between the navigation problem and the Hydropower REPAIR model are as follows:

- Time scales associated with repairs of failures at the lock are generally on the order of hours, days and possibly weeks as opposed to the months and years at power plants;

- The factors affecting usage of the lock are generally treated as a random variable (i.e. vessels arrive at different intervals);

- Seasonal variations exist for vessel arrival frequencies;

- Multiple failure modes are intrinsic to the problem;

The navigation problem is better represented as event-based (driven by the random arrival times of vessels at the lock) as opposed to the period-based hydropower model. A period-based model would not capture the desired behavior, requiring too much ‘lumping’ of information. Under the event-based formulation, each tow can arrive at the lock at any time, and is processed at that time.

MODEL STRUCTURE, CONCEPTS, AND LIMITATIONS

As with the Hydropower REPAIR model, the lock is represented as a hierarchy, consisting of a lock, composed of one or two chambers (main and auxiliary). Each chamber is composed of one or more components as shown in Figure IV-4. There is no particular physical definition or behavior associated with a component. A component is simply something that can fail, and whose current status participates in determining the overall performance of the lock. This concept allows the modeling effort to focus on the specific components of interest for the rehabilitation examination.

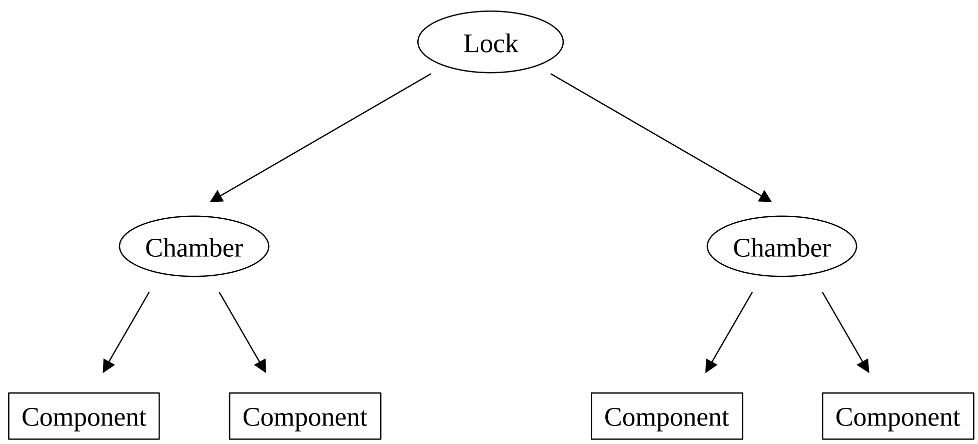

Figure IV-4. Life Cycle Lock Repair Model Architecture

The basic focus of the model is on how rehabilitation of components will affect overall lock performance. Modeling of multiple failure modes is necessary to capture the range of behaviors seen in the real world, as most lock components are not simply either completely functional or completely non-functional.

To handle multiple failure modes in the event-based framework, the concept of component states is used. Each component can occupy, at any given time, one of a set of user-defined states specific to that component. A miter gate, for example, might be in one of three possible states – excellent, poor, and non-operational (see Figure IV-5). A guidewall might be in one of four possible states – very good, medium, poor, and highly degraded.

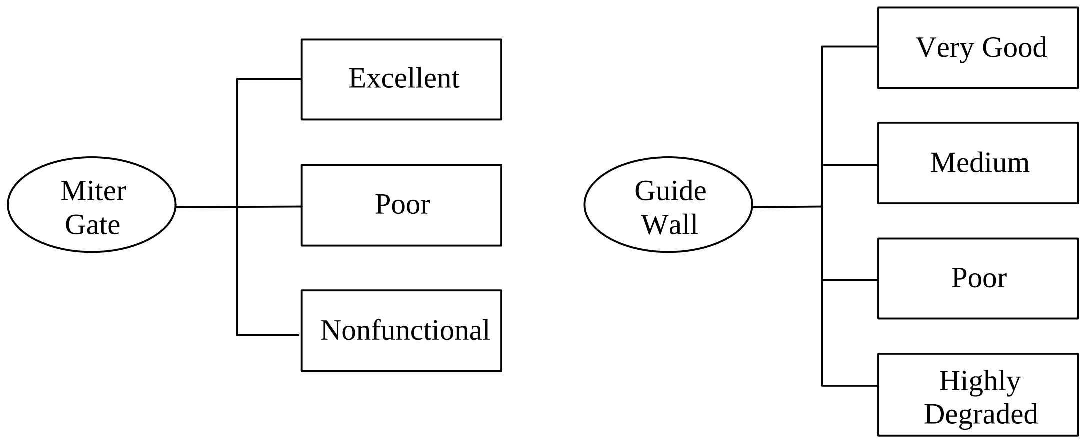

Figure IV-5. Component States

The driving force for moving a component from one state to another state can be either the passage of time, the cycling of the lock (e.g. simply opening or closing of the gates), or be related to a collision with a vessel. Thus, over time, a gate can corrode. It can fail due to stresses associated with repeated opening and closing. A barge can collide with the gate, causing major or minor damage.

The model abstracts this idea to define events under which a component can undergo a particular state transition (failure mode):

- Time – a regular passage of time, in some user-specified constant period (number of hours);
- Lockage – a cycling of the lock, where no damaging collision is possible (if a rowboat hits the miter gate, the miter gate will not be damaged);
- Lockage of a Tow (heavy vessel) – i.e. an event where a damaging collision is possible;

These events are the external factors that affect the lock during the simulation: time passing, and lockage of vessels.

In order to define probabilities associated with a change in state of a component, State transition probabilities are associated with the component for each of the event types (see Figure IV-6). For example, consider a miter gate, in excellent condition. During the lockage of a tow, there may be a probability of .0001 that, on that particular lockage, a severe collision might take place, making the gate non-operational. However, there might also be a .002 probability of a minor collision, placing the gate in poor condition. Transition probabilities are a function of the particular state the component is in. A minor collision to a gate in excellent condition may have a .0001 probability of making the gate non-operational, but if the gate is already in poor condition, the same collision might make the gate non-operational, with a much higher probability of .003. The fundamental idea is that, for a particular event type and a particular component, a set of state transition probabilities can be defined giving the probability that the component will transition to the target state from its current state, when the event occurs.

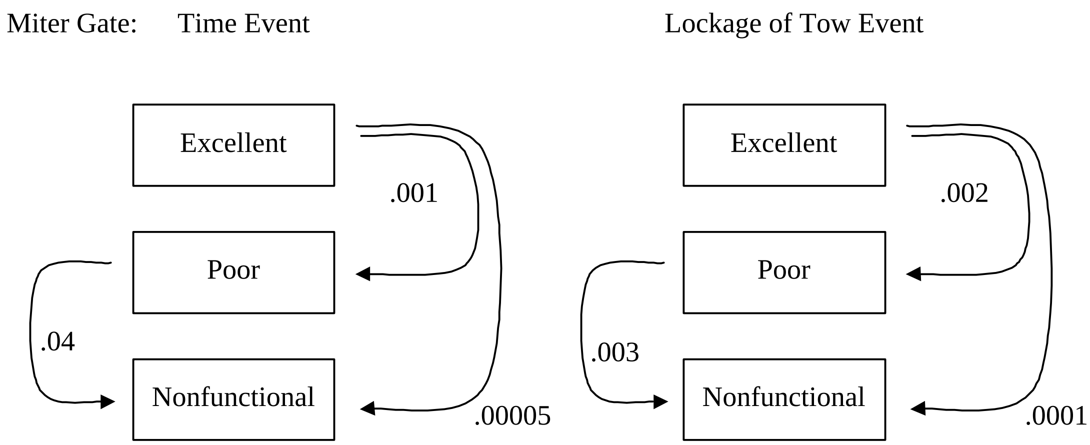

Figure IV-6. State Transition Probabilities

Note that the state transition probability is a function only of the component state and event. There is no concept of degradation over time, as in the hydropower model, other than through state transitions. Similarly, a rehabilitation or emergency repair incurs a cost and duration, and places the component in a revised state at completion of the rehab or repair. Thus, everything is handled in terms of component states and state transitions.

A repair is associated with each state transition. The repair is carried out after the failure mode, and consists of a cost, duration, and a final state. The final state can be the same as the initial state, indicating a situation in which we simply incur cost and delay, but do not really make a significant enough change to move to a different state. Different repair policies can be defined, such that, after a particular failure, one of a set of repairs is chosen (e.g. maximal repair, minor repair, “quick fix”, etc.).

A rehabilitation is a planned event, setting the state of one or more components to new values at a given time during the simulation. Associated with each rehabilitation event are the duration for which the chamber will be unavailable, and the cost.

The state of the components of the chamber affects the performance of the chamber, expressed as the service time (time it takes for the chamber to lock a vessel through). It is recognized that this can be a very complex inter-relationship amongst the components, and a full description of the possibilities is difficult to generalize. A simplified structure, making use of a performance penalty associated with each component state, is utilized. For each chamber, a baseline service time distribution is defined (by mean and standard deviation). Each component, depending upon its state, contributes an additional amount of time as a performance penalty beyond the baseline. Thus, a component in excellent condition would contribute a very small or zero performance penalty, whereas a component that is completely failed, forcing the chamber to shut down, contributes a very large performance penalty (beyond the duration of the simulation, effectively closing the chamber).

Model Processing

As the simulation progresses, tows are generated based on user input of seasonal arrivals at the lock. A tow approaches the lock, and enters a queue. When it arrives at the head of the queue, it enters the lock, with service time determined by the state of lock components. The auxiliary chamber is used if the main chamber is unavailable.

At each lockage event, and at regular periodic time events, the state transition probabilities are tested, by generating a random number from 0 to 1 and comparing it to the probabilities for the possible failure modes for the current event and component state. If a failure takes place, the component state is updated, the associated repair is invoked, and the chamber is out of service for the duration of the repair. The performance penalty for each component is summed to get the total performance penalty for the chamber, and the associated service time is calculated. After the calculated service time, the tow leaves the lock, making it available for the next tow.

If a rehab event takes place, the chamber is taken out of service for the specified duration of the rehab, at the time of the rehab. At the end of the rehab, the component states are set to their post-rehab values.

The process is repeated for the duration of the simulation, and for repeated iterations. Statistics are generated on the repair cost, delay cost to vessels, length of queues, number of failures, and percent of time the chambers are utilized.

Model Inputs

The hierarchy of chambers and components within the lock must be defined. For each component, the allowable states are defined, and the state transition probabilities and repairs associated with each event type are specified. If many states and components are defined, this can lead to a large amount of required data entry. Data entry is simplified and organized through the MS-Access user interface, which provides a number of alternative views of the data.

The user defines a distribution of types of tow, by percentage, and identifies tow characteristics, in terms of baseline lockage times for each tow type for each chamber. Monthly statistics on total tows are provided, to allow for seasonal variations. Because the model is run as a life cycle model, a simplified capability to provide growth in the number of tows over time is also provided.

Alternative rehabilitation plans are defined as events at given times, with associated cost and duration of chamber closure. Associated with each event are one or more changes in component state, the net result of the rehab.

The user must provide interest rate information, and simulation control information (length of simulation, number of iterations, output control).

Outputs

The model provides standard reports describing the input data, the results of each simulation run, and comparisons between baseline and rehab plan runs. A sample report showing typical output information for a single iteration test is presented on the following page.

Applications

The model has been applied only on test data at this point, and has not yet been used in a real-world situation.

NAVIGATION RISK

10/15/98 8:02:29 PM

Scenario: SP1 **Description: Test Scenario policy 1** **Run Date: 4/9/97 12:08:18 PM**

	Average	Maximum	Minimum	Standard Deviation
NUMBER OF TOWS	1866	1866	1866	0
DELAY PER TOW	1901.34	1901.34	1901.34	0.00
TOTAL REPAIR COST	51,182.12	51,182.12	51,182.12	0.00
DELAY COST	1,351,802,765.09	1,351,802,765.09	1,351,802,765.09	0.00
MAXIMUM DELAY	4989.27	4989.27	4989.27	0.00
UPSTREAM QUEUE	6	6	6	0
DOWNSTREAM QUEUE	3	3	3	0
TIME FAILURES	0	1E-38	0	0
LOCKAGE FAILURES	2	2	2	0
TOW LOCKAGE FAILURES	24	24	24	0
% LOCK USED	47.99%	47.99%	47.99%	0.00%
% LOCK REPAIR	4.34%	4.34%	4.34%	0.00%
% LOCK REHAB	1.20%	1.20%	1.20%	0.00%
REHAB COST	6,720.22	NA	NA	NA

Navigation Risk *Page 1 of 1*

LEVEE REPAIR MODEL

The Levee Repair Model was developed in response to a request from the Jacksonville District to IWR for assistance in risk-based economic analysis associated with the Herbert Hoover Dike Major Rehabilitation Study. The model development process provides an excellent example of spiral development, and usage of the model to coordinate a variety of inter-disciplinary factors required for the study. Development was started in January of 1997, with an initial version available in September of 1997. Subsequent modifications led to a completed version in July of 1998.

Herbert Hoover Dike is an earthen embankment surrounding Lake Okeechobee in southern Florida. The lake is in the path of Gulf and Atlantic hurricanes during hurricane season, leading to hurricane-induced storm surges. The embankment is subject to seepage and piping under conditions of large headwater differential. The potential for breaching of the dike through seepage or piping-induced failure of a portion of the levee exists. Such failure would lead to inundation of areas protected by the dike, with attendant damages associated with residential and agricultural land uses, and affected populations. The problem has many probabilistic aspects, including:

- Frequency and type of hurricanes;
- Lake stage variation over time;
- Tailwater distribution over time;
- Probability of breaching of different portions of the embankment;

The problem involves hydrologic, geotechnical, and economic issues. The Jacksonville District had done a good deal of work in these areas, developing basic data and understanding of the individual arenas, but had not developed an integrated model to combine them. Accordingly, initial efforts were oriented towards developing a common understanding of, and terminology for, the problem. This was accomplished through repeated iterations of a problem-framing document, a detailed written analysis of how the problem was to be viewed, and how the model would operate. This set of documents allowed all parties to have input to the model development process and to review the abstractions, assumptions, and data requirements that would be involved. Once sufficient agreement was obtained, model development was initiated. During the course of model evolution revisions to the framing document were made as new insights and techniques of handling specific aspects of the problem were developed.

Model Structure, Concepts, and Limitations

Rehabilitation alternatives are directed at reducing the likelihood of breaching of the levee. Breaches are anticipated to form in portions of the levee in response to large hydraulic head differentials between the lake side and the tailwater side (outside of the levee). Lakeside elevation is a combination of static lake stage, which varies slowly based on normal inflows and outflows to the lake, and hurricane storm surge, which varies rapidly (hours) in response to the passing of a hurricane. The susceptibility to breaching is a function of the condition of the levee, which varies along its length.

For purposes of modeling of the geotechnical behavior of the system, Hoover Dike has been divided into a number of *reaches*, and reaches are further subdivided into *components*, which are contiguous sections of the dike. The component is the part of the system that is susceptible to breaching. As with the other models, failure and repair take place at the component level. Breaching behavior is modeled in a stochastic fashion, through Probability of Unsatisfactory Performance (PUP) functions, giving the probability of a component breach as a function of lake stage at the component. Lake stage is composed of static lake stage, and, if a hurricane exists, hurricane surge. The impact of rehabilitation alternatives is reflected primarily through modification to the PUP functions associated with component breaching, i.e. a rehabilitation alternative will result in a component PUP function showing a lower probability of breaching for the same lake stage.

If a component breaches, it can breach in one of two modes – low velocity (smaller breach) or high velocity (larger breach) with differing associated times and costs of repair, and damages. Breaching behavior is dependent upon the height of tailwater behind the component. If this results in a head differential greater than a critical level, then a high velocity breach is expected. Otherwise, a low velocity breach occurs.

A breach of a component can result in the inundation of one or more areas outside the levee, referred to in the modeling effort as damage cells (see Figure IV-7). Monetary and non-monetary impacts are associated with the inundation of these damage cells. The economic damages associated with a damage cell are a function of the land use within the damage cell, lake

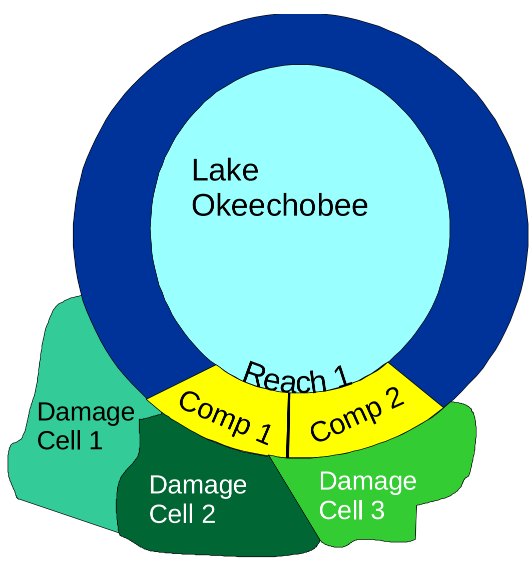

Figure IV-7. Levee Model Architecture

stage when a breach occurs, type of breach (high/low velocity), and time since previous inundation (due to persistence of agricultural crop damages, sometimes over a period of 10 years following a flood). The problem is complicated further because there is not a simple one-to-one relationship between a component breach and the damage cells that get inundated. The same damage cell can be flooded from breaches in more than one component. The model stores user-entered functions that determine the associated impacts of breaches as a function of static lake stage.

A period-based modeling approach was selected, based primarily on the continuous hydrologic data for lake stage, which does not lend itself to an event-based formulation. A 4-season model is used to capture variations in hurricane probabilities and the state of crops during different times of the year. This formulation does restrict the number of hurricanes allowed to one per period, but statistics show that the probability of more than two hurricanes in the 6-month hurricane season is very low, thus this is not seen as being limiting for the Levee Repair model.

An initial effort at developing synthetic lake stages through an autocorrelation model did not reproduce historical lake stage statistics well. An autoregressive moving average model (ARMA model) was then developed from historical lake stage data, to provide the needed synthetic static lake stage hydrology.

Hurricane season in the study area is from June 1 through November 30. The historical record indicates that the tracks of tropical cyclones affecting Lake Okeechobee can be divided into two basic categories:

- From the southeast (Atlantic storm), producing the greatest surges along the southeast quadrant of the lakeshore

- From the southwest (Gulf of Mexico storm), producing the greatest surges along the northwest quadrant of the lakeshore.

A methodology for estimating the storm surge at each component based on the different types of hurricanes was developed by the Jacksonville District. This method estimates storm surge at an index location, and then uses functional relationships between all other locations and the index location to get the desired surge at a component.

Provision is also made for reduction in lake stage if a breach occurs, due to the loss of water through the breach. Although this effect is minor, given the very large volume of the lake, it is included for completeness of representation.

Economic impacts include repair cost, O&M costs, rehab costs, and economic damages based on land inundation in a damage cell, associated with a breach. In addition, provision is made for non-monetary impacts of damage cell inundation. Effects of inundation are handled by curve lookup based on functions giving damages (or non-monetary effects, such as population affected) in a period as a function of static lake stage.

Model Processing

The overall flow of the model is relatively straightforward. The user initially sets all of the needed input parameters (simulation duration, number of iterations, interest rate, etc.). The model is then run for the required number of cycles and iterations. In each iteration, the behavior is as follows:

a) Determine the static lake stage in the current cycle, based on the ARMA model;

b) Determine whether a hurricane takes place in the current cycle, based on input hurricane probabilities;

c) Test each component, in turn, for breaching, based on stage at the component, which is determined as static lake stage plus storm surge (if a hurricane is present). Once the stage has been determined, a PUP value is determined based on function lookup. This is compared with a generated random variable (0 to 1), to determine if a breach takes place. If a breach condition is found, the velocity of the breach is determined by obtaining a random value of the tailwater from an input triangular distribution of tailwater at each component. The head differential is calculated and compared with an input *critical value*–if the head differential is greater than the critical value, a high velocity breach condition exists, otherwise it is a low velocity breach;

d) If a breach takes place in the cycle, determine the associated impacts (monetary and non-monetary damages), based on function lookups, and accumulate them. The effect of prior inundation is accounted for by applying reduction factors to damages associated with the current cycle, based on damage reduction curves input for specific land uses.

This process is repeated for each cycle of the iteration, and for the number of iterations requested.

Model Inputs

The model is heavily data-intensive. Information is required on reaches, components, damage cells, and their inter-relationships, as well as extensive information giving the functions that define damages associated with breaches.

The physical system is described by defining reaches, components within reaches, and damage cells associated with inundation of components. For each component, repair cost for reach (high and low velocity), tailwater triangular distribution, and information associated with surge and lake stage reduction under breach is required. PUP functions of probability of breach as a function of lake stage are also required for each component. The appropriate function must be specified as an initial condition for each component (post-repair PUP is taken to be the same as pre-repair PUP).

Seasonal information requirements include the number of days in the period, the probability of any hurricane, and the probability of a Gulf or Atlantic hurricane (given a hurricane).

Four parameters of the ARMA model are required: the mean, the serial correlation, the standard deviation, and the mean of the error term. As well, an initial lake stage to start the process, and a maximum and minimum lake stage, are required.

A frequency distribution for storm surge for each hurricane type at a designated index component is required, in the form of surge vs. exceedence probability.

Costs associated with a rehab plan are specified as a spending schedule, giving the cost in specific cycles associated with the rehab (which may include quarters prior to actual construction, to capture E&D costs, etc.). For each component that is rehabbed, post-rehab values for the component PUP function, repair cost, and tailwater distribution parameters (minimum, maximum, and most-likely tailwater) are required. [Some rehab alternatives are oriented towards changing the tailwater behind the component.]

General information is required for each simulation run, and, as with the other models, is organized into 'scenarios'. For each scenario, information is needed as to the duration of simulation, number of iterations, interest rate, identification of rehab plan, start year and base year of the simulation, critical head differential (for distinguishing between high and low velocity breach), initial water surface elevation, as well as various parameters that determine the level of detailed output to be provided by the simulation.

Model Outputs

Model output provides statistics on the number of hurricanes, number of breaches, and associated monetary and non-monetary impacts, based on the input parameters. Information can be presented in reports or graphically. The following insert is the Scenario Description Report. It contains input Scenario information and simulation calculated result information. The user can also select graphs of component breaches, and lake stage statistics, with a variety of formatting and display options. Graphs of scenario output such as Iteration statistics as seen in Figure IV-8 can be displayed and exported to other formats.

Applications

The model has been used by the Jacksonville District to provide and economic evaluation of major rehabilitation plans for the Herbert Hoover Dike facility in Southern Florida. The model has been in use at the Jacksonville District, in its final form, since July of 1998.

Scenario Description Summary

15-Oct-98 *5:17 PM*

Scenario: T-1000 **Description:** 1000 Iterations **Run Date:** 8/21/98 2:44:25 PM

Plan:	None	**Initial Lake Level Mean:**	15	**General Lake Statistics**		**Simulation Settings**	
Start Year:	1997	**Initial Lake Level Std Dev:**	1	**Critical Tail Water:**	13	**Iterations:**	10
Base Year:	2000	**Static Lake Level Mean:**	14.379	**Max Lake Level (ft):**	24	**Cycles:**	200
Hurricanes:	Yes	**Static Lake Correlation:**	0.535	**Min Lake Level (ft):**	10	**Interest Rate:**	0.07125
O & M Multiplier:	1	**Static Lake Std Dev:**	1.5153	**Lake Moving Average:**	-0.4856	**Seed:**	0

	Average Cost ($)	**Min Cost ($)**	**Max Cost ($)**	**Std Dev**	**Std Error**	**Rehab Cost ($):**	0
Repair:	839,851	0	2,795,496	922,155	291,610.9		
O & M:	34,949,223	33,803,296	36,259,059	771,873	244,087.7		
Damage:	126,273,058	0	302,220,238	106,764,933	33,762,036.4		
Total:	162,062,132			106,771,706	33,764,178.0		

Scenario: T-1000D **Description:** 1000 Iterations debug **Run Date:** 8/6/98 10:08:25 AM

Plan:	None	**Initial Lake Level Mean:**	15	**General Lake Statistics**		**Simulation Settings**	
Start Year:	1997	**Initial Lake Level Std Dev:**	1	**Critical Tail Water:**	13	**Iterations:**	1000
Base Year:	2000	**Static Lake Level Mean:**	14.379	**Max Lake Level (ft):**	24	**Cycles:**	200
Hurricanes:	Yes	**Static Lake Correlation:**	0.535	**Min Lake Level (ft):**	10	**Interest Rate:**	0.07125
O & M Multiplier:	1	**Static Lake Std Dev:**	1.5153	**Lake Moving Average:**	-0.4856	**Seed:**	0

	Average Cost ($)	**Min Cost ($)**	**Max Cost ($)**	**Std Dev**	**Std Error**	**Rehab Cost ($):**	0
Repair:	606,856	0	4,046,990	657,373	20,788.0		
O & M:	26,677,690	24,494,490	28,969,487	749,822	23,711.5		
Damage:	100,851,090	0	602,742,033	102,646,266	3,245,959.9		
Total:	128,135,635			102,651,110	3,246,113.1		

Scenario: Baseline **Description:** Baseline, new pups 6/4/98 **Run Date:** 8/28/98 12:13:33 PM

Plan:	None	**Initial Lake Level Mean:**	15	**General Lake Statistics**		**Simulation Settings**	
Start Year:	2000	**Initial Lake Level Std Dev:**	1	**Critical Tail Water:**	13	**Iterations:**	200
Base Year:	2000	**Static Lake Level Mean:**	14.379	**Max Lake Level (ft):**	24	**Cycles:**	200
Hurricanes:	Yes	**Static Lake Correlation:**	0.535	**Min Lake Level (ft):**	10	**Interest Rate:**	0.07125
O & M Multiplier:	1	**Static Lake Std Dev:**	1.5153	**Lake Moving Average:**	-0.4856	**Seed:**	0

	Average Cost ($)	**Min Cost ($)**	**Max Cost ($)**	**Std Dev**	**Std Error**	**Rehab Cost ($):**	0
Repair:	22,353,522	0	130,167,847	23,716,763	1,677,028.4		
O & M:	28,565,400	26,639,228	31,028,196	874,976	61,870.2		
Damage:	85,310,598	0	589,193,178	91,551,163	6,473,644.8		
Total:	136,229,521			94,577,301	6,687,625.1		

Hoover Dike *Page 1 of 2*

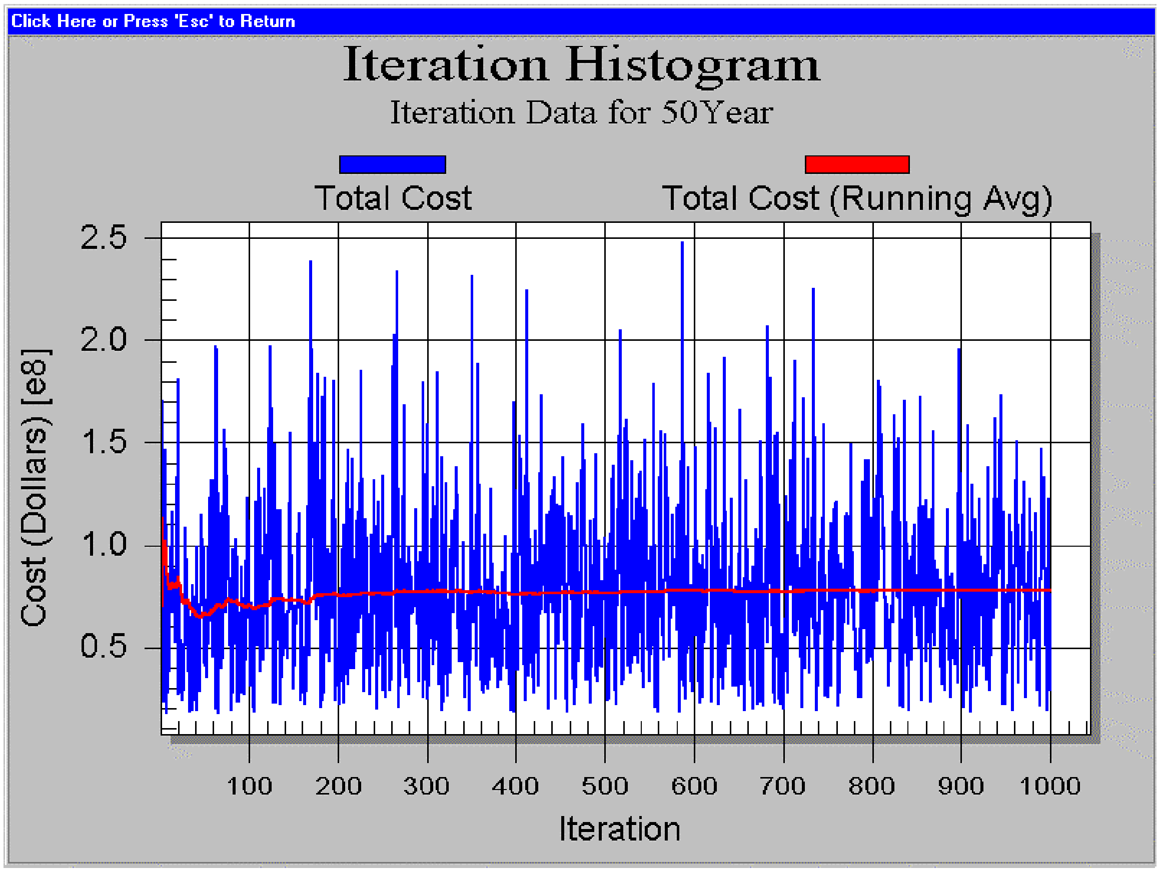

Figure IV-8. Iteration Histogram

WATERWAY SYSTEM SIMULATION

The Waterway System Simulation model was developed in response to a request from the Galveston District to IWR for assistance associated with a series of Section 216 feasibility studies of navigation improvements to the Gulf Intracoastal Waterway (GIWW) in Texas. The initial study area was from High Island to the Brazos River, with subsequent portions of the waterway to be examined in later studies. The Galveston District desired a flexible model that could be applied to each of these studies, as they were initiated. Work on model development was initiated in February of 1997, and the model was completed and applied to the High Island to Brazos River study area in April of 1998.

The beneficial effects of investments in channel modifications such as widening and bend easing accrue in the form of reduced transportation costs to shippers, thereby producing National Economic Development (NED) benefits. In some areas of the existing channel, tows must slow to safely navigate while in others passing is restricted. These limitations incur additional operating costs and increased transit time. Although there may be some added benefit by improving tow safety, the primary beneficial effect is the reduction in operating costs by reducing transit times.

As noted previously in the discussion of the Life Cycle Lock Repair model, such examinations are best carried out in the context of a waterway systems model. This allows for examination of the impact of investment in one portion of the waterway on overall throughput and reduction in transit time for a complete trip, not simply in the section being improved. While large-scale, detailed, and complex simulation models do exist for the Ohio and Upper Mississippi Rivers, no general purpose model suitable to the scale of the GIWW problem was available, leading to the decision to support model development for use in the initial and subsequent studies. This dictated that the model be sufficiently flexible that it could be applied to different portions of the waterway, with changes based on data inputs. The High Island to Brazos River portion of the waterway does not contain any navigation locks, thus the initial version of the model does not explicitly provide for locks. A revised version is currently under development at IWR that will include additional features, including explicit lock modeling.

The problem is clearly risk-based: arrival and departure of tows from ports happens on an unpredictable schedule, and transit time through the system also varies depending upon traffic and weather. In addition, alternative routes through the system are possible, and a specific route between ports may not always be known in advance.

Initial examination of the problem suggested that a period-based model would be necessary, because of the large number of events that would need to be handled in an event-based model. The level of averaging that would have been required with the period-based model, however, would have made it difficult to develop data and analyze the model behavior. Feasibility tests on an event-based approach showed that a large number of events could be handled adequately. Accordingly, the event-based approach was selected, in large part because it is much more physically based, and easier to interpret.

The GIWW problem is not a major rehabilitation study. There is no concern about degradation, failure, and repair. Rather, channel improvements are designed to provide faster transit times over the existing condition. As such, the model is designed primarily for single-year, rather than life cycle, application, although a simplified capability for growth in traffic (necessary for life cycle modeling) is included.

Model Structure, Concepts, and Limitations

The real world waterway problem is enormously complex. A variety of individual economic decisions are made to determine whether a particular shipment actually moves on the waterway, or by an alternative mode. These decisions are affected by the cost of alternative modes of transportation, long term contracts, short-term demands for commodity movements, and conditions on the waterway. Once on the waterway, weather and traffic are encountered, and each individual tow operator chooses speeds and routes to maximize safety and minimize cost. Conditions change seasonally. Under some circumstances, the number of actual tow boats and barges available for use may limit traffic. Tows may be made up and broken down with different barges during the course of a journey. A tow may contain barges of different commodities. Navigation rules and locking policies come into play. Statistics characterizing the movement of tows exist, but are frequently difficult to interpret and make consistent, and may not provide the required level of detail for a desired analysis.

The GIWW model, as currently formulated approaches this problem through a simplification and abstraction of the problem. Basic assumptions are:

- The waterway is made up of defined reaches, and can be formulated as a link-node network;
- Some of the nodes of the network are ports;
- A small set of tow classes can be used to represent traffic of different types moving on the waterway;
- Seasonal statistics are available on port-to-port trips by tow class;
- Transit time of a tow within a reach is a stochastic variable, based on the tow class, transit rules, and congestion within the reach;
- There is no re-fleeting (making up and breaking up tows en route to their final destinations), and the quantity of tows and barges is not limited;

With this as the basic framework, the model routes each tow through the waterway from port to port.

The waterway network is represented as a node-link system. Each link of the network is referred to as a reach. Reaches have an implied direction of transit (upstream, downstream). Some of the nodes of the network are referred to as ports - those nodes at which trips originate or terminate. Trip statistics are defined in terms of ports, and ports are then associated with nodes of the current network formulation. This approach allows the waterway network to be modified, without requiring the user to change information about trip statistics.

Vessels (tows) move along the reaches of a waterway network, from origin port to destination port. Each such traverse is a trip, and the set of reaches for a trip is termed a route.

A tow, for the purposes of the model, is any vessel/barge combination for which transit times in a reach can be defined, and with which an operating cost can be associated. The model does not specifically take into account physical sizes of tows. Rather, it uses the concept of tow classes, a statistical grouping of like tows, with common operating costs. Statistics on port-to-port trips and reach transit times are associated with each tow class, and each individual generated tow takes on the characteristics of its associated tow class.

A given tow can be either light (barges empty) or loaded (barges full). This distinction between light and loaded is necessary because of different behaviors of each type of tow, in terms of transit time and congestion and transit rule behavior. The term 'tow type' refers to the combination of tow class and either light or loaded, i.e. tow class 1 - light is a single tow type, as is tow class 1 - loaded.

A route is a path through the network, from origin port to destination port. Routes are defined as unique, contiguous paths of reaches between ports, and are uniquely numbered. Note that the route from port 1 to port 2 may be different from the route from port 2 to port 1. Moreover, there may be multiple routes between the same port pairs (if there are loops in the network). In the current implementation of the model, routes must be externally defined in terms of reaches, numbered, and stored in the database. An automatic route generator will be incorporated in the forthcoming version of the model.

The route chooser stores the probability that a tow will choose a given route between ports. The user can set the probability of the tow moving along each route - but the sum of route probabilities between a given port pair for a tow type must equal 1.0. When a particular tow enters the waterway system, the model chooses the particular route taken to the destination port based on the stored probabilities.

Transit time of a tow through a reach is determined based on sampling from a triangular statistical distribution stored in the database by tow type and direction of travel. Improvements to the waterway are expressed as changes to the parameters stored for reach transit time.

Transit rules describe what can happen when tows simultaneously occupy the same reach. Each reach will have one of four transit rules: no transit rule; no overtaking in same direction; no meeting; or single tow allowed in the reach at a time. Depending upon the particular transit rule in effect for a reach, the exit time for a tow is adjusted based on other tows in the reach to preserve the appropriate queuing behavior within the reach, allowing a tow to wait for other tows to proceed.

Model Processing

The model is event-driven. It generates and maintains a queue of times when events take place, adds and deletes information on this event queue as needed, and processes each event in chronological order. Events handled by the model include start of a period; entry of a tow into the system; movement of a tow into a reach; and exit of a tow from the system. As each event is processed, the current time is moved forward to the next event in the queue, and that event is processed, until the simulation duration has been completed.

At the start of each period of the simulation, the model uses the stored trip statistics to generate trips between ports, getting a list of tow types and trips, sorted by departure time [period start event]. It then processes each trip in the list. As a tow enters the system [tow entry event], the model chooses the route that will be traversed, end-to-end, based on the input route choice probabilities for the particular tow type on the particular route. There are no internal routing decision points in the model - once a tow has entered the system, the reaches it crosses to get from origin to destination are determined based on the stored route that has been chosen.

The model routes all tows through the system, reach to reach along their pre-defined routes, as the appropriate event [tow move event] takes place. Thus, rather than route a single tow through the entire system, all tows are being moved one reach at a time, in turn, based on the appropriate time at which a tow enters or leaves a reach (as stored in the event queue).

As each tow enters a reach, the time that the tow will spend in the reach is determined, based on the state of the reach (and system) at the moment of entry. This sets the time that the tow will exit from the reach (or from the system, if it reaches its destination). Thus, as soon as a tow enters a reach, calculations are made to determine when it will exit, and the exit time is placed on the event queue, which is always maintained in sorted order, so that events are processed in proper time sequence.

The calculation of tow exit time involves examination of raw reach transit time, congestion, and transit rules. The total transit time of a tow in a reach is determined by first determining if the reach is congested (are other tows in the reach or nearby?). The travel time in the reach is then obtained by sampling from a user input triangular distribution of reach transit times for the particular reach and tow type. Depending upon the congestion conditions for the reach, the distribution is sampled from either the entire distribution, or the upper or lower portion of the distribution.

If transit rules (are tows allowed to pass each other in the reach?) are in effect for the reach (again as set by user input data), the exit time of a tow is determined by whether or not it can pass other tows, moving in the same or opposite directions. Thus, if transit rules are in effect, a tow cannot leave a given reach until other tows that entered previously have left. In this manner, the exit time of the tow from the reach is determined as the 'raw' transit time (based on the congestion calculations) plus the time that the previous tow leaves the reach. A number of different transit rules can be specified, and the actual calculation of exit times involves additional complexity, involving headway between tows (minimum time separation).

As each tow transits a reach, statistics are accumulated for the tow and reach. As a tow leaves the system, its total end-to-end transit time, and associated operating cost, are determined.

This process is repeated for all tows in a period, all periods of the simulation, and the requisite number of iterations of the simulation. At the end of the simulation, statistics are written to the database and to one or more ASCII files.

Model Input

The user must specify the waterway network, defining reaches and nodes, and associating certain nodes with ports. This can be done graphically from the user interface seen in Figure IV-9.

Tow classes must be defined. With ports and tow classes defined, trip statistics, giving the mean and standard deviation of port-to-port trips by tow class during a period, can be entered.

For each tow class, light and loaded, and transit direction, a triangular distribution of reach transit times, giving minimum, maximum, and most likely transit time in the reach (in hours), must be set. These are the parameters that are changed by navigation improvements.

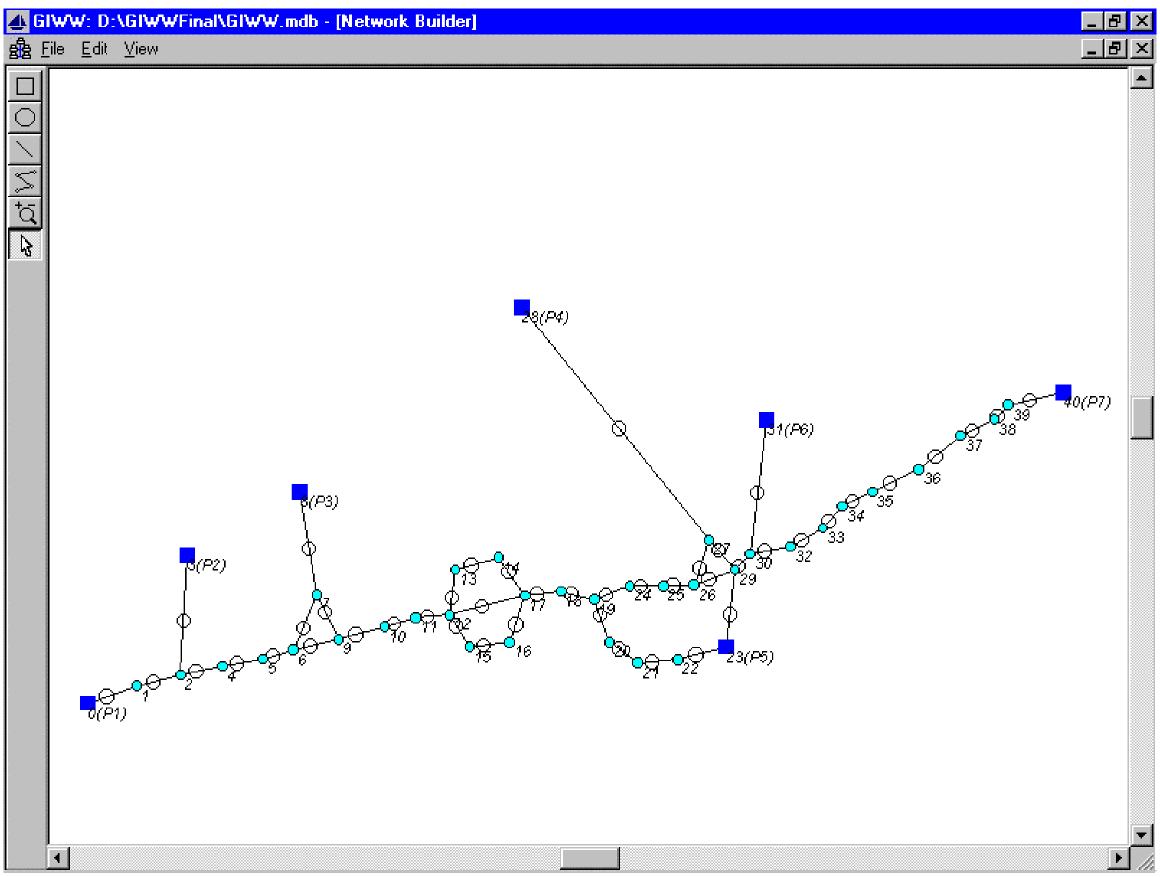

Figure IV-9. Network Builder

At present, the possible port-to-port routes through the network must be defined externally. This can also be done graphically through the user interface. As noted above, these routes will be defined automatically in the next release. Where more than a single route between ports is possible, the user must assign probabilistic weights, summing to 1, to each route.

Transit rules and congestion factors must also be assigned to each reach.

The model simulates behavior for a user-specified duration, in hours (all time in the model is in hours). The user can set the number and length of periods within a year (e.g. monthly, seasonal models), to reflect different traffic patterns in the waterways at different times of the year. In order to allow for start up of the simulation, a user can input a conditioning period (number of hours), to allow tows to populate the waterway, before starting the actual simulation, for which output statistics are collected.

The input requires a good deal of data, and it is potentially possible to leave out an important data element, for example failing to assign transit time within a reach for a particular tow class. For this reason, a data checking algorithm is included in the model, to insure, insofar as possible, that all needed data items are present for a simulation run.

Model Outputs

There are two primary forms of model output:

- Information stored back into the database;
- Detailed ASCII output files;

The information stored back into the database is used by the user interface to display individual and comparative results for scenarios. The ASCII output files are used for verification of input, and detailed exploration and debugging of model behavior.

At present, there is no graphical output associated with the model. The next release will include graphical output visualization capabilities.

Statistics are also provided on the number of tows generated, the number of tows entering and exiting the system, the number of tows used in the conditioning process, and the number of tows remaining in the system. Additionally, reach-specific output is also provided, giving the average and standard deviation of total tow hours spend in each reach, associated cost, and count of number of tows occupying the reach.

Scenario Summary

Scenario	Scenario Description
Causeway_1998	Causeway, base year 1 month

Trip Alternative	Transit Time Alternative	Route Choice Alternative	Period Alternative	Transit Rule
OneYear	Causeway	Without	Year	NoRules

Simulation Length	Iterations	Interest Rate	Start Year	Base Year	No Overtaking Time	Conditioning Hours
750.000	30	7.13%	1,998	1,998	0.100	20.000

Congestion SD Factor	Growth Factor	Seed	Run Date	Kernel Version	Computation Time (sec)
1.000	1.000	17	1998/04/11 22:44:15.00	0.990	577.00

Simulation Results

Average Tows	SD Tows	Minimum Tows	Maximum Tows
1,724.367	47.458	1,625.000	1,834.000
Average Hours	SD Hours	Minimum Hours	Maximum Hours
21,494.351	854.733	19,226.624	23,972.924
Average Cost	SD Cost	Minimum Cost	Maximum Cost
$3,232,033.01	$126,131.39	$2,900,535.38	$3,592,794.55

Applications

The Waterway System Simulation model has been applied to the Galveston District in Texas to assist in feasibility studies of enhancements to its Intracoastal Waterway to improve navigation times of commercial vessels. In April of 1998, the model was applied to the study of the High Island to Brazos River area.

V. ISSUES AND DISCUSSION

EVOLUTION OF THINKING/KNOWLEDGE

The opportunity to work on related problems over a period of years has led to an increase in skills, superior tools, and definite changes in the way that the problems are viewed and the models structured. The basic underlying data-driven structure, and the model architecture (user interface, database, simulation kernel, reporting and graphics modules) have held up well. Object-oriented approaches have also been valuable, allowing much re-use between different models, and good opportunities for physically based problem conceptualization. The decision to use C++ has also proven worthwhile, primarily in terms of computational efficiency and ability to use certain internal programming structures that are readily available in that language. It has, however, led to relatively less accessible code.

For rehabilitation-type problems, a hierarchical component-based structure has also served well. The need to separate out the cost of rehabilitation from the impact on components is also clear – it is not always possible to associate a cost solely with a single component.

Event-based modeling has much to recommend itself as a method of approaching these problems. It allows for less averaging of the problem, and a more physically based model. Interpretation of results of an event-based model is easier than for the more ‘lumped’ period-based models. The developers were surprised that event-based modeling could be applied to a problem such as waterway systems modeling, with so many events to process. Computational efficiencies have allowed for use of event-based modeling approaches where it would otherwise seem too time-intensive.

It is clear that multiple failure modes are appropriate for most modeling efforts, and allowing only operational and non-operational modes, as in the Hydropower REPAIR model, is limiting. However, dealing with the combination of both state-based transitions and time-based degradations can create both conceptual and data complexities which, to date, have not been well solved.

The models have a good deal of internal complexity. The problems they address are not simple in themselves, and formulating them in a risk-based context to be solved by Monte Carlo simulation adds to both the difficulty of understanding and of parameterizing the model. Thus, having a good user interface and good visualization and display capabilities for results are essential.

The user interface must naturally lead the user into the problem structure, and should simplify, insofar as possible, the data entry and editing process. This is not always easy, and the developers are not entirely satisfied with the model interfaces as they now exist. A good deal of discussion, negotiation, and modification went into the user interface development. Vast amounts of effort can be placed on the user interface. Experience in the development process was that very little testing or data development could be done without an initial user interface. As the first view of the model, the user interface can be the most irritating, and it is often difficult to get past problems with the user interface to get to the actual functioning of the model. Because each model has a different underlying structure, and the interface needs to properly reflect that structure, it was not possible to come up with a single solution that applied equally to all models, and could be re-used simply.

A further point of importance is that the models typically involve a large amount of data. This is often developed externally, and available in spreadsheet or database form, as was definitely the case for the Waterway System Simulation and Levee Repair models. The underlying MS Access database of the models has capabilities for importing many types of data, but this requires knowledge and understanding of Access software, and is not typically available from the model-specific user interfaces. In fact, in the course of the modeling efforts, much of the original data was entered in this fashion (through direct dealing with the underlying databases), with the user interface capabilities being used for editing and making wholesale changes. It is simply too time-consuming to enter computer-resident data by hand. This is a problem that has not been well solved to date, and bears further examination, so that the user interface can provide data import capabilities.

For development and testing, it is essential that the ability to examine the internal workings of the model in great detail be available. Many internal calculations are made to get to a few numerical outputs, and it is important to verify that statistics are being handled properly, random numbers are truly random, and that the model in general is behaving as it should. The models developed to date have only limited visualization capabilities, instead relying upon output (under user control) of large numbers of detailed ASCII files, which can then be subjected to analysis to view the internal workings of the model. In fact, during model development, it was only through analysis of these data files by the model developers that many problems were uncovered and corrected. Such instrumentation is essential for these types of model. At the same time, an improved method of graphically visualizing the internal workings of the model, and a less onerous method than analyzing each output file individually, would be very desirable. Again, this is model-specific, thus difficult to develop general solutions.

GENERAL VS. CUSTOM TOOLS

As noted previously, the initial thrust of development efforts was to create a single, general-purpose, easily used tool for many risk-based analysis programs. Experience led to the idea of tools for classes of problems (navigation, hydropower, etc.). Even this approach is somewhat limiting, as the specifics of a problem for one study may be quite different from those of another study. The approach, throughout development, has been to generalize each specific tool as much as possible, allowing for site-specific differences through input data. At the same time, the particular nature of each problem under study must be examined, and, if necessary, new tools must be adapted or created to suit the specifics of the problem.

The selection of C++ as a programming language, and the fairly sophisticated use of capabilities of MS-Access, means that modification or new development requires a certain set of programming skills. Alternative approaches, using general-purpose simulation environments (such as Stella) are possible, but carry with them certain disadvantages as well: significant learning curve, difficulty of making models data–driven, difficulty of distribution to a wide audience, and requirements to work within the problem context made available by the simulation environment.

COMPLEXITY ISSUES

The problems being examined in risk-based analysis are inherently complex. They involve engineering, and economic behavior. Recognition of the 'system-wide' effects, such as the role a lock plays in a waterway system, further complicates the problem, and makes the choice of a system boundary more difficult. Frequently, inter-disciplinary aspects come into play, as in the Hoover Dike application, involving economists, hydrologists, and geotechnical specialists. Meaningful statistics that describe the behavior, and show the impact of changes, must be devised and calculated. Data for the models must be obtainable, and, in some fashion, relatable to available real-world numbers. The concepts and techniques of risk-based analysis and Monte Carlo simulation may themselves be unfamiliar.

All of these factors must be synthesized in the model. A meaningful model, then, is likely to have some significant complexity if it is to reasonably simulate real-world conditions. At the same time, the model must not be so complex as to be self-defeating – too hard to understand, too difficult to obtain data, or too difficult to run.

Some significant learning curve is to be expected when dealing with these models. Users need to become familiar (and comfortable) with the general techniques and approaches of risk-based analysis and Monte Carlo simulation. Then, the specific problem context, method of abstraction, and calculations must be understood, as well as the limitations associated with the model. Finally, the details of operating the model, developing the input data, verifying model behavior, and analyzing the output data, must be learned.

The models developed and reported on here are not simply "fill in the blanks" procedures. They demand a good deal more involvement and understanding on the part of the user, and this should be made clear at the beginning of any investigation.

DEVELOPMENT ENVIRONMENT

It has become very clear, during the course of these efforts, that development in the context of a real-world problem is enormously valuable. Of the four models developed to date, the Hydropower REPAIR and Life Cycle Lock Repair models were developed essentially in the abstract, i.e. without being a part of a specific study. The Hydropower REPAIR model was designed, initially, to replace existing spreadsheet formulations. For the Hydropower model, there was a target given by previous solutions, that is, to provide the same or increased capability as the spreadsheet solutions, and when the initial Hydropower REPAIR model proved to be 100 times faster than spreadsheet solutions, with much greater ease of use, the concept was validated. The Life Cycle Lock Repair model did not initially have such a target, and the formulation was developed in a more abstract context.

The Waterway System Simulation and Levee Repair efforts were problem-focused, with clear needs defined for particular studies. The opportunity existed to develop the models so that they would be oriented to the problems at hand, while keeping as much generality as possible within the framework. Importantly, the development process for these models was such that problem understanding, model development, and data development all proceeded hand-in-hand. The above-noted problems relating to learning curve were thus lessened, and the models became a focus of the inter-disciplinary efforts, providing the needed synthesis of many parts of the respective studies. 'Ownership' of the models was much broader, in the sense that all of the participants had an opportunity to understand the issues as the models were being built, review the interim outputs, and influence the development of the model.

This approach also demonstrated that such problem-specific models can be developed at moderate cost and reasonable time-frame, within the context of an individual study. The fact that all of the models shared a common framework, and were built using object-oriented techniques, facilitated the development in this regard.

VI. FUTURE DEVELOPMENTS

Future enhancements and extensions to the models will be done primarily through specific project applications, where changes are needed, or improvements can readily be made. The Waterway System Simulation model (GIWW) is currently being extended under a separate project.

For all the models, the main arenas of improvement desired at present are in the areas of data import/export and results visualization. As noted above, the large amounts of input and detailed output data require improved handling methods.

For the Hydropower REPAIR Model, two areas of desired enhancement are clear: the inclusion of multiple failure modes, and operation on a shorter period, rather than the current yearly cycle. Both will allow much more flexibility in model application and use.

As noted above, the GIWW waterway model is currently undergoing a variety of modifications to make it more general and easier to use. Modifications include increased visualization, simplified input, lock behavior, and more sophisticated economic analyses. Further enhancements to the GIWW model may come about in subsequent studies on the part of the Galveston District, but these are not expected to require major modifications.

The Levee Repair model can serve as the basis for other applications involving levees or dam safety, but no specific applications have been developed as yet.

Enhancements to the Life Cycle Lock Repair Model await a real-world application, which will point out the needed arenas of improvement.

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APPENDIX A

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APPENDIX A: HYDROPOWER REPAIR MODEL

The Hydropower REPAIR application is a period based economic evaluation tool that performs a risk-based analysis of components in a three tiered system. The purpose of the system is to analyze the projected total output of a hydropower facility due to the implementation of a scheduled rehabilitation plan for the base components. Rehabs made to base components on a time schedule may reduce future repair costs as well as reduce total downtime in comparison to the facility deploying no rehab plan.

Hydropower Repair is a menu driven system consisting of graphical entry forms, graphic displays, and reporting features. The interface is generated with a mixture of Microsoft Access and Visual Basic programming to feed information into the underlying database.

A graphical approach to data entry has been implemented for this application. This method is quick and easy to use, while maintaining simple data entry screens that are intuitive. The data that is required for establishing the physical idiosyncrasies of the facility are minimal but yields a diverse quantitative analysis with tremendous amounts of data for viewing. Many facilities (studies) can be entered into the application, but to make the interface clearer, a single facility is selected upon startup that limits data entry to the current facility. Only information relative to the selected facility, such as scenarios, can be accessed.

The application is organized into four distinct categories for entering, manipulating, and generating data. These categories are:

- Facility Structure
- Risk Elements
- Scenario Data
- Simulation Results

A Hydropower facility and all of its components can be created through the use of the graphic interface. For example, if the user wanted to create a facility called ‘Prospect1’, the Add button would be clicked from the Select Study form that opens when the application is began. This launches an entry form that collects reference information about the facility. The user would enter ‘Prospect1’ as the name, enter a brief description, and select an Energy Generated Function for the facility. Upon clicking the OK button, a graphical editor for entering other facility structure data is opened.

The graphical editor seen in Figure A-1 displays each tier of the facility along with their relationships. The graphical editor displays the facility as the upper tier, units as the intermediate tiers, and components as the base tiers. Units are created for the facility by highlighting ‘Prospect1’, clicking the right mouse button, and selecting Add from the popup menu. When the Unit form opens, information that describes the unit is entered and saved. The name ‘Unit 1’ is entered for the unit, along with a Unit Capacity (kiloWatt), Group ID, and Critical Code.

Components of the units are entered the same way as units are entered for the facility. After selecting 'Unit 1' and clicking the right mouse button, a popup menu is displayed with the option to Add. Selecting this option opens a Component entry form where names and properties are assigned. This level consists of the working parts of the facility. In this example, Turbine and Generator are entered as the components of each unit. The properties of each component consist of repair costs, repair time, post state performance, and operation and maintenance information.

Through the graphical editor, several standard Windows features such as double-clicking and drag-and-drop capabilities are utilized to reduce the amount of keyboard entered information. Selecting an item and clicking the right mouse button displays a menu that allows quick addition, removal, or cloning of the selected item. Components can be cloned to the same unit or another unit by selecting the component, and dragging-and-dropping it onto the Unit that it is to be assigned. Double-clicking an item accesses the data of each item. Once the properties have been invoked, they can be altered and saved.

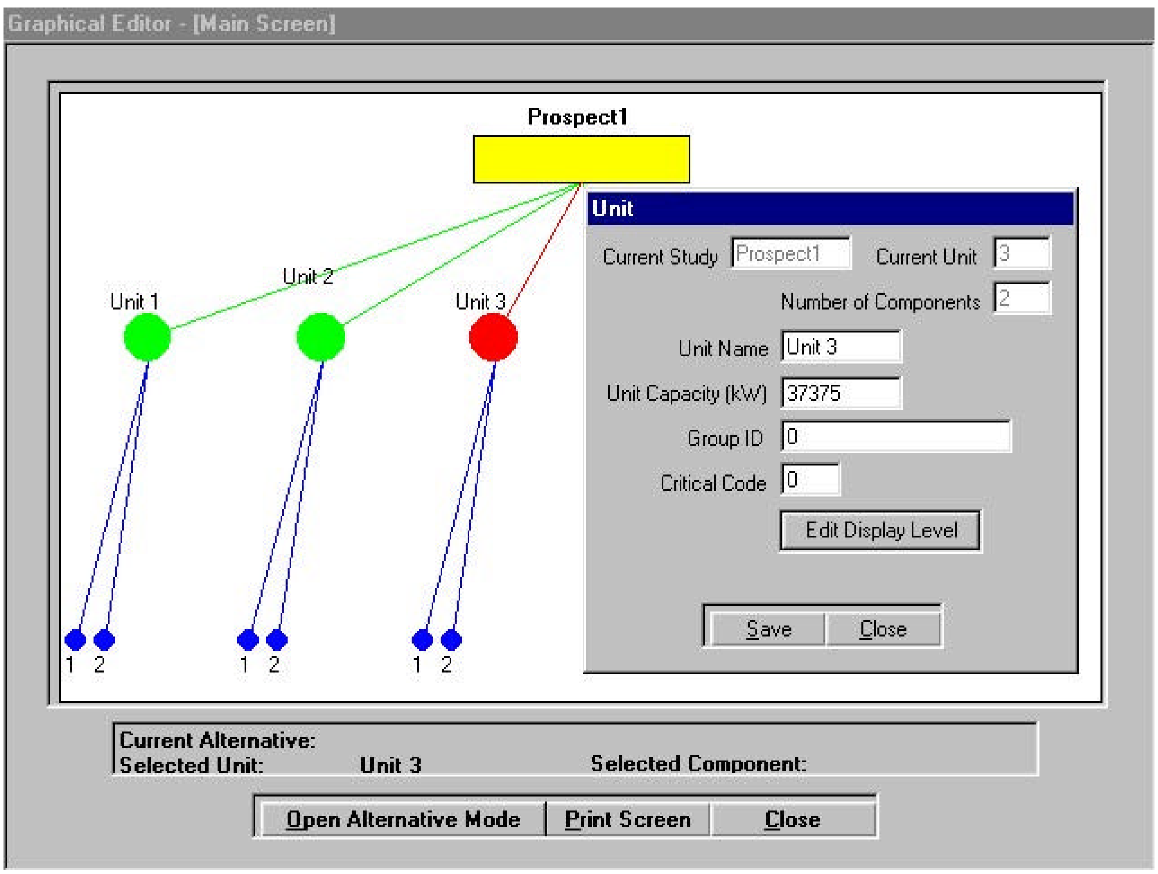

Figure A-1. Graphical Editor Form

Incorporated into the graphical editor are the abilities to create, edit, and remove rehab plans. Rehab plans consist of a cost schedule, facility start year, unit expenditures, and component post rehab information. For any facility, clicking the 'Open Alternative Mode' opens a selection form that displays all of the existing rehabilitation and allows new plans to be created. For 'Prospect1', there are no rehabilitation plans, so clicking the Add button opens a Rehab Plan information form where a name, description and start year are assigned. For 'Prospect1', a rehab plan named 'Alt1' has been created.

After the editor has entered the alternative mode, the diagram of the 'Prospect1' becomes color-coded to represent which elements have had rehabs assigned to them. Each unit and component has rehab information that must be entered. Rehab data is entered by double clicking a unit or component. In addition, a Rehab Cost Schedule must be created for 'Prospect1'. This contains a yearly expenditure for 'Prospect1'. To create a 'Rehab Cost Schedule', the dollar sign that appears in the upper right hand corner of the diagram must be clicked. This opens a form where expenditures are entered by year.

Risk elements for 'Prospect1' should be entered before the physical structure of the facility. This is because functions are entered into many of the entry forms of 'Prospect1'. Risk elements encompass all of the function data that the simulation references during execution. The simulation process uses the risk information to determine costs and performance of the facility over a life cycle. Risk elements include:

- Current Energy Functions
- Dependable Capacity Functions
- Probability or Unsatisfactory Performance (PUP) Functions

A Current Energy Function (Figure A-2) was associated to ‘Prospect1’ when it was created. This function is used to determine the energy output of the facility at different operation levels. Only one Current Energy Function is assigned to ‘Prospect1’.

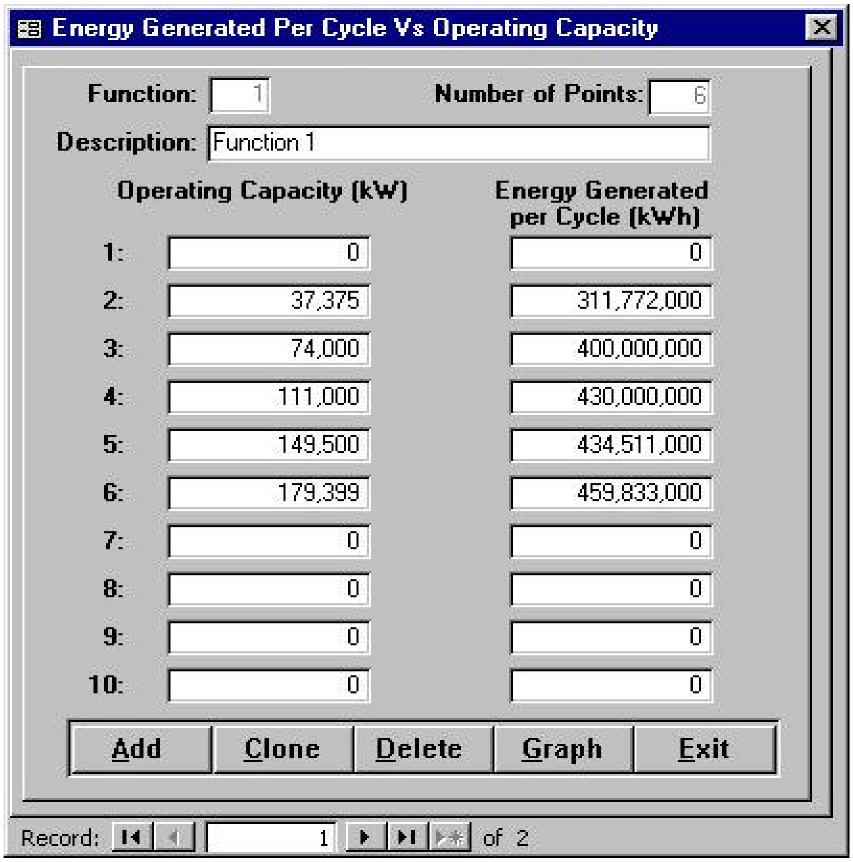

Figure A-2. Current Energy Function Management Form

Like Current Energy Functions, only one Dependable Capacity Function exists for each facility. The function is entered by selecting Dependable Capacity from the Risk menu. It is used by the simulation to determine the reliable amount of kiloWatts produced by ‘Prospect1’. It is entered through the Dependable Capacity Management Form seen in Figure A-3.

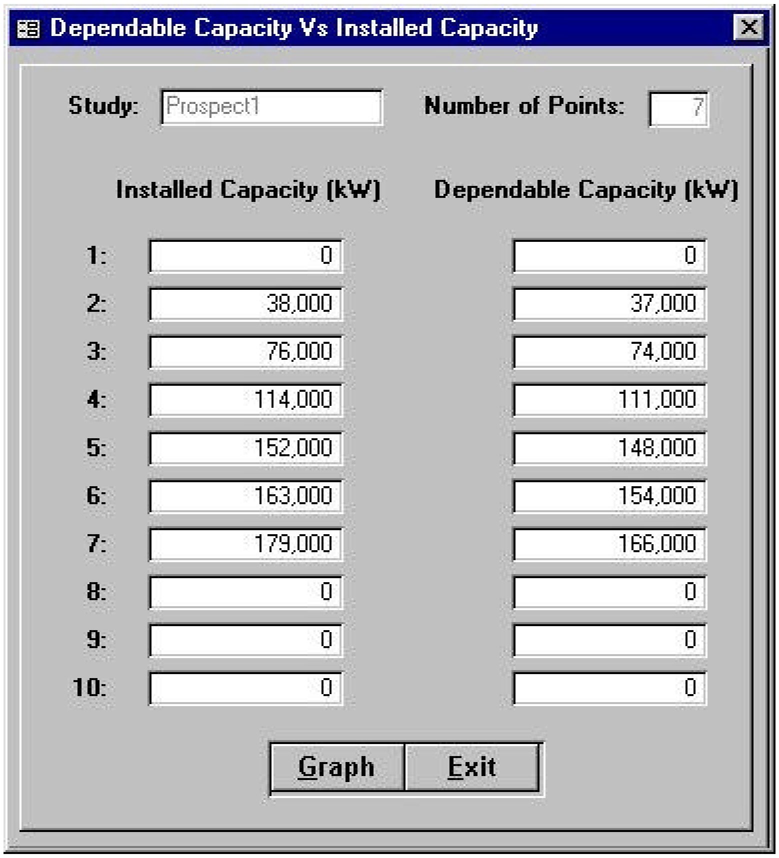

Figure A-3. Dependable Capacity Management Form

PUP functions are assigned to components of 'Prospect1' to yield initial, post repair, and post rehab performance levels during simulations. They are managed by selecting PUP Functions from the Risk menu. Clicking the Graph button launches a function builder that allows manipulation of data points through use of a mouse. Functions can contain up to 10 coordinate points. They are entered through the PUP Function Management Form seen in Figure A-4.

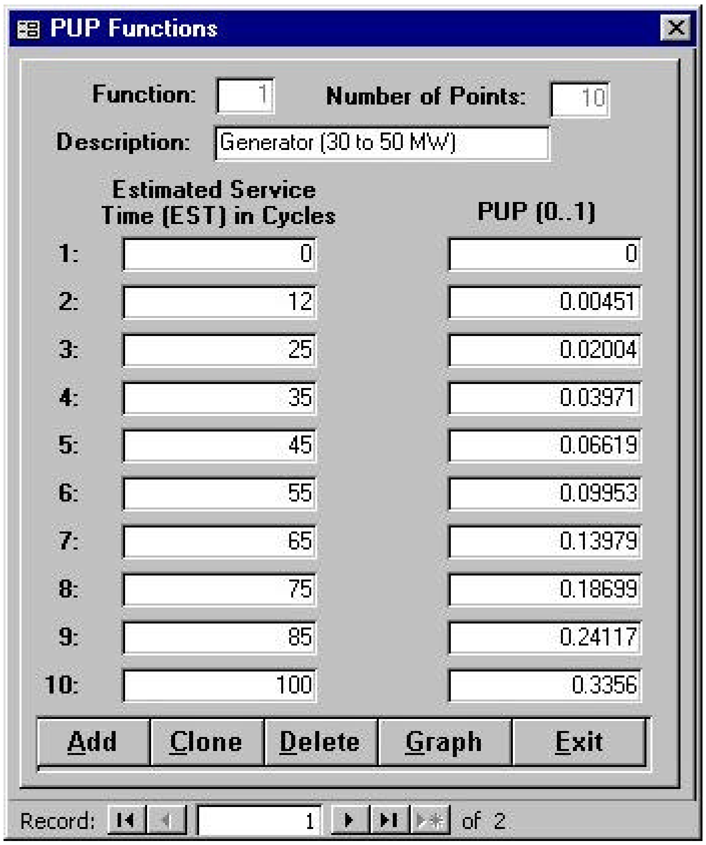

Figure A-4. PUP Function Management Form

The next set of data to enter for 'Prospect1' is Scenario information. Scenarios consist of information that is pertinent to the simulation process. Scenario information is managed by selecting 'Manage Scenarios' from the 'Scenarios' pull-down menu. This launches the Scenario Management form seen in Figure A-5. Once the fields of the form have been entered, clicking the 'Run Scenario' button initiates the simulation process.

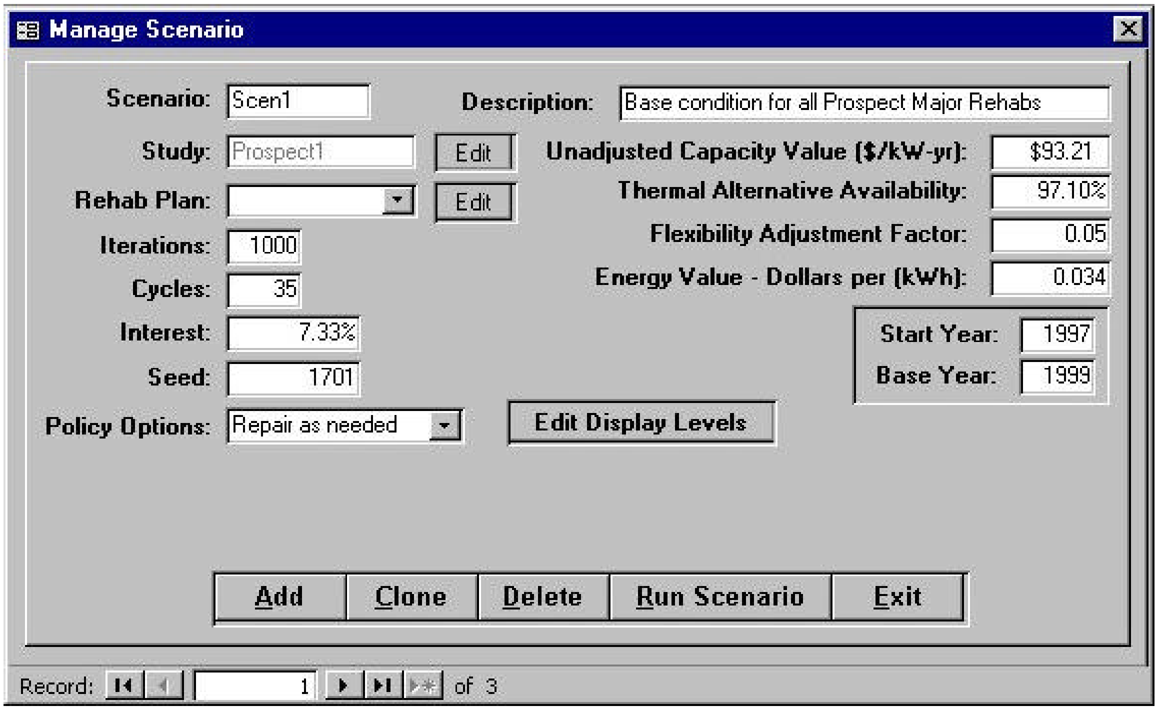

Figure A-5. Scenario Management Form

Included in the Scenario menu is a Scenario Description Report. This report displays all of the information that is entered on the Scenario form along with the physical structure and rehab plan data. Included on the report are the Dependable Capacity, Current Energy Generated, and PUP Functions. In this case, the report displays a summary of the 'Prospect1' input data with a focus on the rehab information.

The focal point of the application is to provide feedback on costs and outputs for the facility. Once a scenario for 'Prospect1' has been processed, the application supplies graphical displays of simulation calculated rehab data for the following statistics:

- Repair Cost
- Operation and Maintenance Cost
- Total Cost
- Dependable Capacity
- Current Energy Generated

These statistics can be displayed as percentage by cost interval or as cost by iteration. Both of these options are selections that can be made from the Results menu. The Simulation Iteration Graph (Figure A-6) includes the capability of graphing the cost, average cost, and confidence interval by iteration. Convergence is seen when all options are selected for the graph.

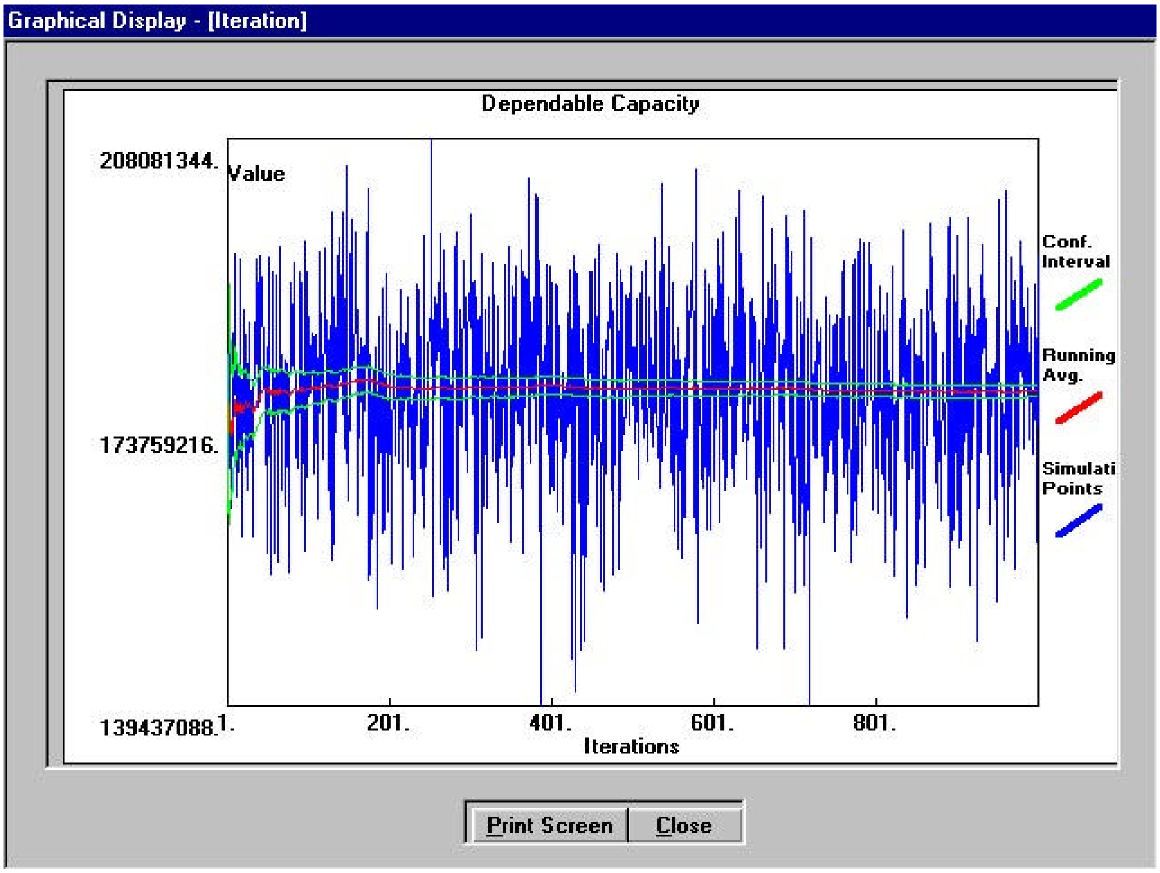

Figure A-6. Simulation Iteration Graph Form

Two reports exist that yield a comparative analysis of simulations for ‘Prospect1’. They are the Scenario Simulation Output Summary and All Reports. The All report includes unit and component level costs in addition to the information that they both report. Both reports contain a cost comparison to a Base Scenario with no rehab plan. The following information can be obtained from either report:

- Capacity Benefits
- Energy Benefits
- Repair Costs
- Operation and Maintenance Costs
- Investment Costs
- Net Benefits

The following is a sample of the Scenario Simulation Output Summary Report. The base scenario is ‘Scen1’ and it is compared to two other scenarios, each posing a separate rehab plan. The report displays a great amount of data for possible rehabilitation plans including gross, and net benefits, and a benefit-cost ratio. These reports complete the analysis for the ‘Prospect1’ analysis.

Scenario Simulation Output (Summary)

01-Oct-98 *2:06 PM*

Scenario Description **Date**	**Study**	**Capacity Benefits** Average Max/Min/STD	**Energy Benefits** Average Max/Min/STD	**Repair Cost** Average Max/Min/STD	**O&&M Cost** Average Max/Min/STD	**Investment Cost** Average	**Net Benefits** Average	**B/C Ratio** Average Max/Min/STD
Base Condition								
Scen1	Prospect1	**$177,470,299**	**$214,934,006**	**$13,837,509**	**$4,810,826**			
Base condition for all Prospect Major Rehabs		$208,081,344	$219,762,142	$26,425,124	$6,112,833			
10/1/98 2:00:11 PM		$139,437,095	$189,577,847	$4,139,445	$3,282,711			
		$11,125,369	$3,290,873	$3,658,955	$488,870			
Scen2	Prospect1	**$177,597,955**	**$214,756,892**	**$10,457,551**	**$3,932,224**	**$6,712,437**	**($2,503,335)**	
Recondition all turbines		$200,596,556	$218,854,618	$21,069,295	$5,038,292			
		$147,045,133	$185,901,319	$2,231,497	$2,661,075			
10/1/98 2:01:50 PM		$9,094,549	$3,167,918	$3,347,353	$450,394			
Scen3	Prospect1	**$216,565,822**	**$224,727,866**	**$3,709,420**	**$2,296,527**	**$18,459,201**	**$43,072,569**	
Replace turbines, rewind and uprate		$228,039,517	$227,421,720	$13,805,475	$2,738,273			
generators		$189,910,791	$201,498,256	$0	$1,623,747			
10/1/98 2:05:09 PM		$7,374,704	$2,689,963	$2,503,789	$147,312			

APPENDIX B

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APPENDIX B: LIFE CYCLE LOCK REPAIR MODEL

The Life Cycle Lock Repair Model, known as the Navigation Repair Decision Support System, is a discrete-event life-cycle simulation model created to explore risk-based economic analysis of rehabilitation at a lock. The focal point of the system is to analyze and assess the monetary benefits that accumulate over time due to the reduction in vessel delay produced by a alternative rehabilitation plans.

The Navigation Repair application is a menu driven system designed for a 32-bit operating system. The foundation of the system is a Relational Database Management System in union with a Monte Carlo simulation process. The interface is designed with many features that make data entry simple and efficient (such as color-coded fields and a graphical input data editor). Other elements of the application include Input Data Reports and Simulation Output Reports.

Data in the model has been organized into disjoint sets to eliminate the need to re-enter information for each simulation run. The nature of the model calls for two primary data sets to be entered before a simulation can be executed, the physical structure and the rehab data.

The physical data consists of descriptive information organized in a three tiered hierarchy of structures, along with related information that describes the facility performance based upon usage over time and repairs. The physical data set consists of the following elements:

- Lock
- Chambers
- Components
- Component State Transitions
- Failure Modes
- Service Distributions
- Repair Options

The rehab data set is used to calculate the facility performance that results from investing time and money into incremental upgrades or routine maintenance to components for reliability. Rehab data consists of the following elements:

- Rehab Plans
- Scheduled Chamber Maintenance
- Post Component Rehab Performance

After initial use of the application, the physical structure data set will not be altered significantly, justifying the isolation of rehab data from physical data. To produce an analysis of many rehab plans for a lock, only a small amount of data in addition to the physical data will be necessary. The creation of a new plan and scenario are all that are required.

To simplify the data entry process and lessen the amount of confusion that may occur, the application forces the user to select a lock to work with while entering information into the database. This selection applies only to the physical, rehab data sets and input data reports; the simulation data and simulation reports are independent. To change to a different lock or create a new one, choose "Select Lock" from the File menu pillar. To demonstrate the use of this system, a walkthrough for entering a new lock and dam into the application will be discussed. From the Lock selection form (Figure B-1), click the Add button and Enter a Name and description for the new Lock. In this demonstration, the lock name will be 'LD26'. After entering the lock information, the 'LD26' becomes the selected lock for the application.

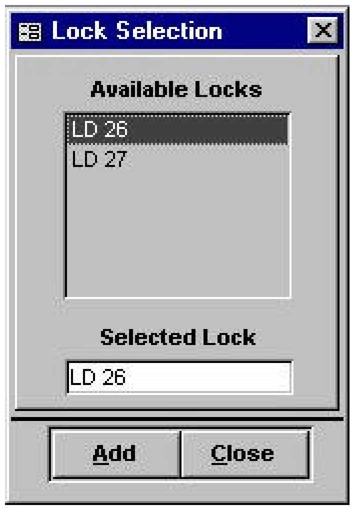

Figure B-1. Lock Selection Form

The layout of the entry forms is based upon the relationships among the data. With the significant amount of data that the system requires, a strategy of showing one to many relationships in entry forms was implemented to assist in data comprehension. Entry forms such as the Chamber Management Form (Figure B-2) illustrate this method. On this form, chambers can be created or deleted from 'LD26'. To create a chamber for 'LD26', click the Add button on the Chamber form. Create a main chamber by selecting Main in the chamber field. An auxiliary chamber can be created by selecting Auxiliary in the chamber field. After making a selection, the chamber is populated with all existing service distributions. Only the standard deviation and mean need to be entered for the each service distribution of the chamber.

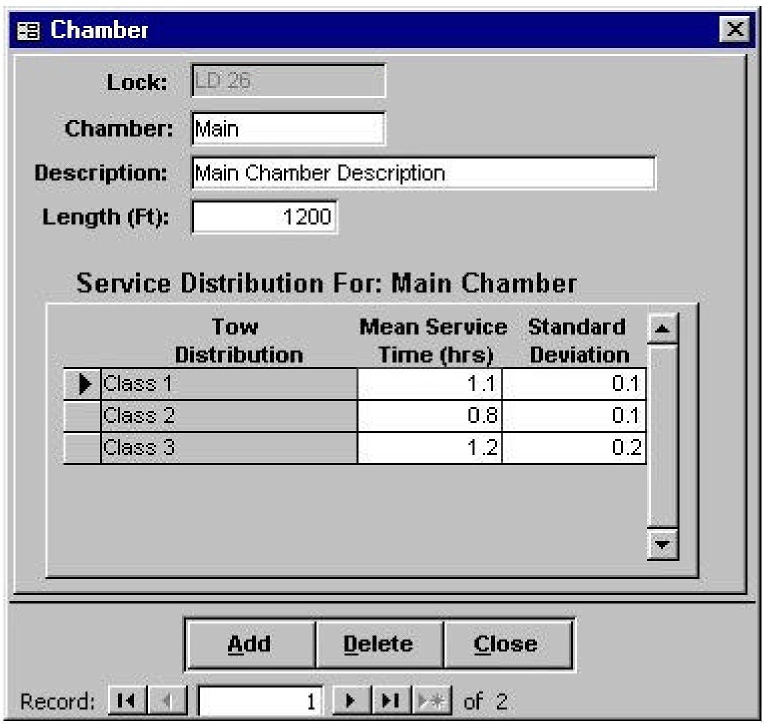

Figure B-2. Chamber Management Form

After creating the chambers, components can be entered. The Component Management Form (Figure B-3) contains the ability to create and edit components along with establishing the Transitional States of the component for each chamber of 'LD26'. Component states are a finite set of distinct performance levels that a component may shift to from its initial state to its post rehab/repair state. Each state has a penalty assigned to it that is used to estimate the hours of downtime that a component may experience during repair. Clicking the Add button creates a new component for the chamber. States for the component are entered by typing the state name and penalty into the blank record in the center of the field. Once all of the component states have been entered, an initial state is assigned to the component.

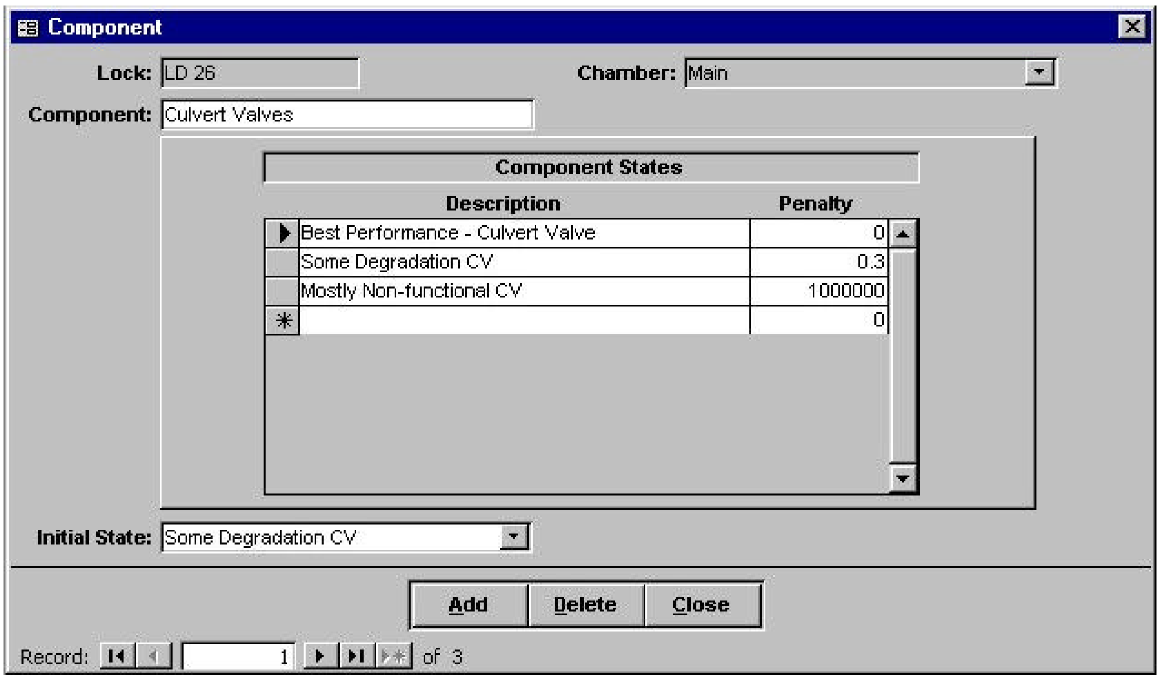

Figure B-3. Component Management Form

After all Components and Component States have been entered, failure modes and repairs can be established for 'LD26'. Component State Transition probabilities for a given event are established on the Component State Transitions Management Form (Figure B-4). From here, events (Failure Modes), post event states, and probabilities for migrating to the post event states are correlated with each component state. Also, for each Failure Mode, a repair strategy is specified for each policy. Failure modes are created by entering an event, rehab, post UP mode state, and PUP. Repair information consists of a policy, cost, down time, and a post repair state. When a failure mode occurs, the repairs that can be made are based upon the repair option selected on the scenario form. Repairs for 'LD26' are created by placing the cursor on the Failure Mode that repairs will apply, then entering a repair policy, a repair description, cost, duration of repairs, and a post repair state. Repair policies must be established prior to assigning repairs.

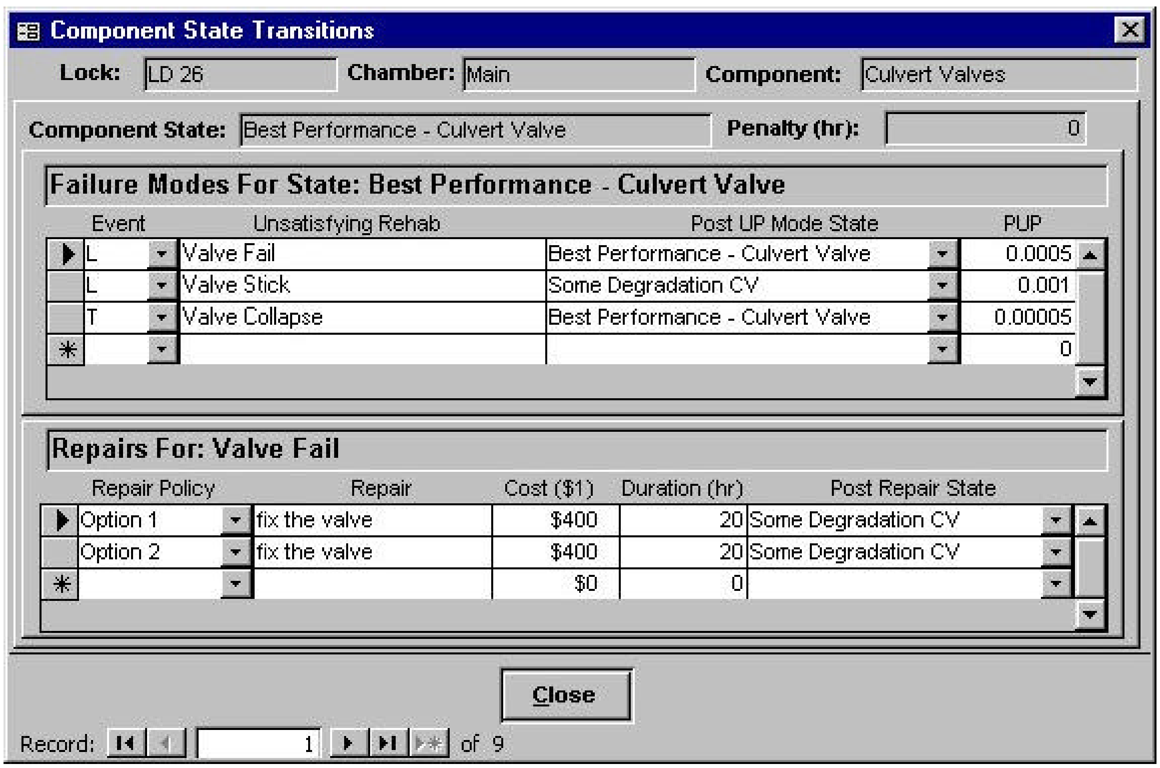

Figure B-4. Component State Transitions Management Form

This concludes the physical structure of 'LD26'. Rehab data is the next set of information to be entered. Rehab data as stated earlier consists of three subsets of data:

- Rehab Plans
- Scheduled Chamber Maintenance
- Post Component Rehab Performance

Data entry for this set of data is accomplished through the use of three forms, one for each subset. Like the physical data forms, the rehab forms display information in a relational hierarchy, which clarifies data during entry.

Rehab plans are applied to the entire lock and each of its chambers. Entering a rehab plan for ‘LD26’ propagates that plan to each of its chambers, so no data entry is required on the chamber level. To enter a rehab plan for ‘LD26’, select Lock from the Rehab menu pillar. On the Lock Rehab form, enter a name and description for each rehab plan of ‘LD26’.

Scheduled chamber maintenance (Rehab Events) are entered for each Rehab Plan of each chamber. This is due to the physical nature of repairs at a lock. When repairs are made, an entire chamber is shutdown and several components are renovated at once to maximize efficiency. To schedule maintenance of a chamber, select Rehab Events from the Rehab menu pillar. On the Rehab Events form (Figure B-5) , enter a description, date, cost, and duration of downtime for a rehab plan of a chamber.

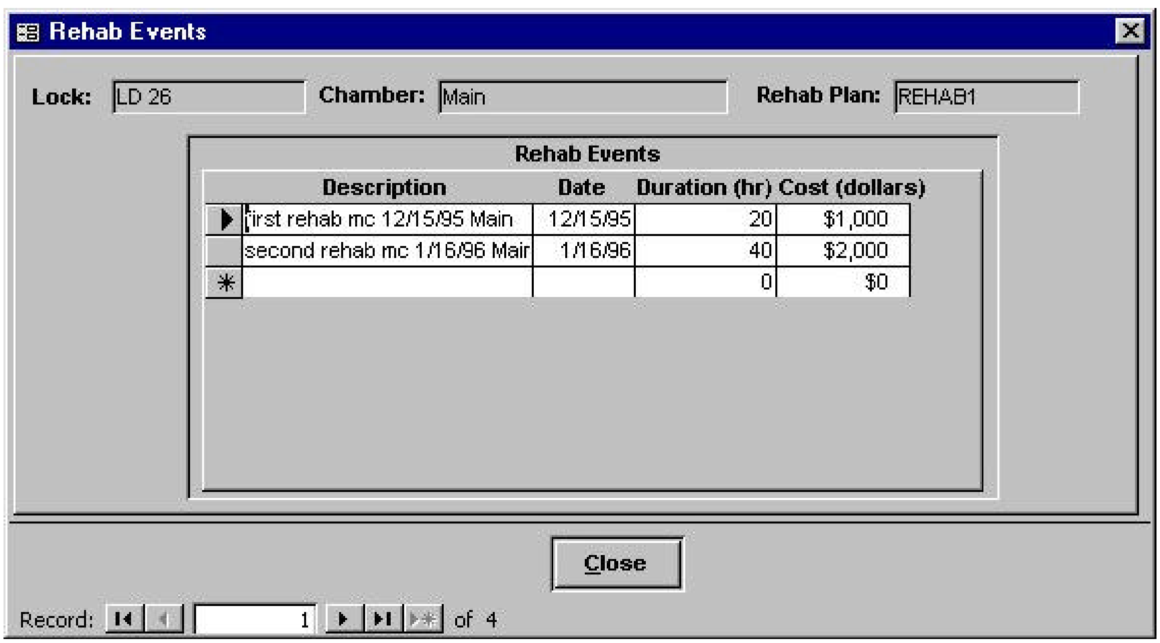

Figure B-5. Rehab Events Management Form

The final element of the 'LD26' Rehab data is Component Rehab information. It encompasses the correlation of scheduled rehab events to components with a post rehab state. Post rehab performance is determined from this association. To enter this information, select Component from the Rehab menu pillar. On the Component Rehab form (Figure B-6) , locate the component and rehab plan to which the event is to be assigned. Select a rehab event and a component state at which the component will be performing after the event occurs.

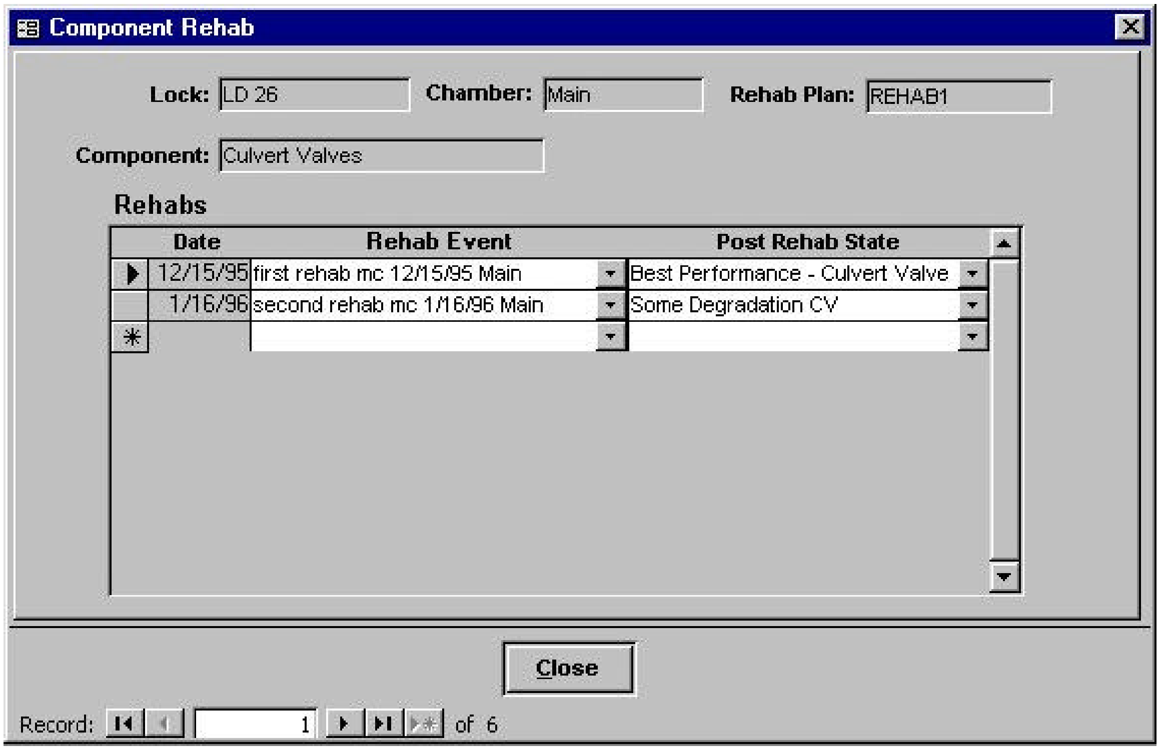

Figure B-6. Component Rehab Management Form

Once the rehab and physical data sets have been completed for ‘LD26’, a scenario can be created to run the Life Cycle process. They are created and edited on the Scenario Management Form (Figure B-7). Scenarios contain pertinent information that the simulation utilizes to forecast lock performance. Simulation control parameters, lock information, service distributions, and other statistics are entered into the scenario to produce a variety of outputs that depict ‘LD26’s’ operation over time. This process tallies cost, traffic, delays, failures, delays, and queue counts for statistic reports.

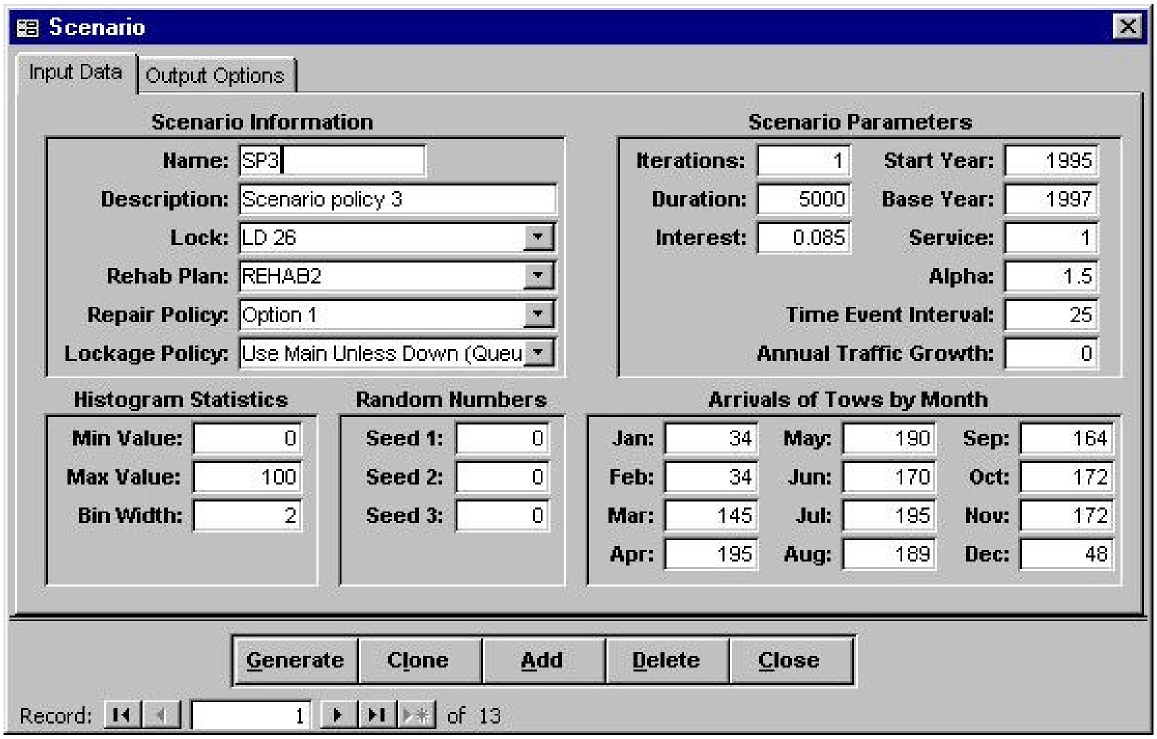

Figure B-7. Scenario Management Form

Navigation Repair contains many reports that are used to display input and simulation data for ‘LD26’. Two reports exist for showing input information, the Lock report and the Lock Rehab report. Each of these reports contains information of the selected lock. The Lock report displays the physical makeup of the system including the following information:

- Lock
- Chambers
- Components
- Component States
- Failure Modes
- Repair Options

Lock: LD 26 First test cut

Chamber: Main Main Chamber Description **Length (ft):** 1200

Component: Miter Gates - 1 **Initial State:** Non-functional

States				Penalty		
Best Performance - MG1				0		
Unsatisfying Rehab	**PUP**	**Event**	**Post UP Mode State**			
minor fatigue A	0.00005	L	Moderate Degradation MG1			
Policy	**Repair**			**Cost ($)**	**Duration (hr)**	**Post Repair State**
Option 1	minor weld			5000	20	Best Performance - MG1
Option 2	minor weld			5000	20	Best Performance - MG1
major fatigue from	0.000005	L	Non-functional MG1			
Policy	**Repair**			**Cost ($)**	**Duration (hr)**	**Post Repair State**
Option 1	install spare			10000	100	Best Performance - MG1
Option 2	install spare			10000	100	Best Performance - MG1
Collision - minor	0.005	LT	Moderate Degradation MG1			
Policy	**Repair**			**Cost ($)**	**Duration (hr)**	**Post Repair State**
Option 1	fix dent			4000	10	Best Performance - MG1
Option 2	fix dent			4000	10	Best Performance - MG1
Collision - minimal	0.008	LT	Best Performance - MG1			
Policy	**Repair**			**Cost ($)**	**Duration (hr)**	**Post Repair State**
Option 1	minor patch			1	1	Best Performance - MG1
Option 2	minor patch			1	1	Best Performance - MG1
Collision - major	0.001	LT	Non-functional MG1			
Policy	**Repair**			**Cost ($)**	**Duration (hr)**	**Post Repair State**
Option 1	install spare gate			10000	100	Best Performance - MG1
Option 2	install spare gate			10000	100	Best Performance - MG1
minor corrosion from	0.0006	T	Moderate Degradation MG1			
Policy	**Repair**			**Cost ($)**	**Duration (hr)**	**Post Repair State**
Option 1	minor fix			1000	15	Moderate Degradation
Option 2	minor fix			1000	15	Moderate Degradation
time degradation	0.0002	T	Non-functional MG1			
Policy	**Repair**			**Cost ($)**	**Duration (hr)**	**Post Repair State**
Option 1	install new gate			15000	150	Moderate Degradation
Option 2	install new gate			15000	150	Moderate Degradation
Moderate Degradation MG1				0.1		
Unsatisfying Rehab	**PUP**	**Event**	**Post UP Mode State**			
minor fatigue B	0.00005	L	Moderate Degradation MG1			
Policy	**Repair**			**Cost ($)**	**Duration (hr)**	**Post Repair State**
Option 1	inspect only			100	1	Moderate Degradation
Option 2	inspect only			100	1	Moderate Degradation
major fatigue	0.000005	L	Non-functional MG1			
Policy	**Repair**			**Cost ($)**	**Duration (hr)**	**Post Repair State**
Option 1	install new gate			15000	150	Moderate Degradation
Option 2	install new gate			15000	150	Moderate Degradation
Collision - major	0.003	LT	Non-functional MG1			
Policy	**Repair**			**Cost ($)**	**Duration (hr)**	**Post Repair State**

Navigation Risk

The Lock Rehab data report contains all of the rehab data for 'LD26'. Each level of rehab from chamber rehab to component rehab events is displayed on this report in an outline format. The breakdown makes the report an easy to read and very organized. The report includes the following information:

- Rehab Plans
- Scheduled Chamber Maintenance
- Chamber Rehab Costs
- Rehab Durations
- Component Improvements

LD 26 First test cut

Main

REHAB1 rehab plan 1

Rehab Date	**Cost ($)**	**Duration (hr)**
12/15/95	$1,000.00	20

Component	**Post Rehab State**
Culvert Valves	Some Degradation CV
Miter Gates - 1	Moderate Degradation MG1

Rehab Date	**Cost ($)**	**Duration (hr)**
1/16/96	$2,000.00	40

Component	**Post Rehab State**
Culvert Valves	Mostly Non-functional CV
Miter Gates - 1	Moderate Degradation MG1

REHAB2 rehab plan 2

Rehab Date	**Cost ($)**	**Duration (hr)**
6/3/98	$400.00	12

Component	**Post Rehab State**
Culvert Valves	Best Performance - Culvert Valve
Miter Gates - 1	Best Performance - MG1

Rehab Date	**Cost ($)**	**Duration (hr)**
6/4/98	$300.00	10

Component	**Post Rehab State**
Culvert Valves	Mostly Non-functional CV
Miter Gates - 1	Moderate Degradation MG1

Auxiliary

REHAB1 rehab plan 1

Rehab Date	**Cost ($)**	**Duration (hr)**
1/16/97	$4,000.00	50

Component	**Post Rehab State**
Miter Gates - ch 2	Moderate Degraded -MG2

Rehab Date	**Cost ($)**	**Duration (hr)**
5/5/98	$800.00	9

Component	**Post Rehab State**
Miter Gates - ch 2	Moderate Degraded -MG2

REHAB2 rehab plan 2

Rehab Date	**Cost ($)**	**Duration (hr)**
4/16/95	$4,000.00	50

Component	**Post Rehab State**
Miter Gates - ch 2	Pretty Good Perfomance - mg ch2

The other reports in the application contain simulation results for 'LD26'. The highlight of these reports is the Scenario Simulation Comparison report. This report displays a comparative analysis of scenarios with rehab plans weighted against a baseline scenario. Gross benefits, net benefits, benefit cost ratio, and other cost statistics are seen to provide a cost analysis for budget preparers. Many scenarios can be selected to appear in this report through a simple interface that is loaded when the report is selected from the menu. To set a scenario as the base condition, select Base under the Scenario menu pillar. Once the Base Scenario form opens, select the scenario to be used as the base. To display the report, select Scenario Simulation Comparison from the Reports menu pillar and a selection form opens to input the scenarios to display in comparison to the preselected base condition. When completed, clicking the Print button displays a preview of the report.

Scenario Simulation Comparison

02-Oct-98 *9:02 AM*

Scenario Description Date	Repair Cost Average Max/Min/STD	Delay Cost Average Max/Min/STD	Rehab Cost Average	Benefits Average	Net Benefits Average	B/C Ratio Average
Base Condition						
full2000	**$54**	**$1,043,179**	**$0**			
	$958	$17,565,905				
policy 3, full output	$0	($10,571)				
9/9/98 10:27:03 AM	$203	$3,497,870				
SP1	**$51,182**	**$1,351,802,765**	**$6,720**	**$51,128**	**$1,350,803,994**	**201006.0666039**
Test Scenario policy 1	$51,182	$1,351,802,765				
	$51,182	$1,351,802,765				
4/9/97 12:08:18 PM	$0	$0				
SP2	**$48,441**	**$1,351,802,765**	**$6,720**	**$48,388**	**$1,350,801,253**	**201005.6587468**
Test Scenario policy 2	$48,441	$1,351,802,765				
	$48,441	$1,351,802,765				
4/9/97 12:08:26 PM	$0	$0				
SP3	**$0**	**($5,319)**	**$3,840**	**($54)**	**($1,052,392)**	**-274.051634637**
Scenario policy 3	$0	$0				
	$0	($5,319)				
8/18/98 1:40:18 PM	$0	$0				

Navigation Risk

Other simulation statistics for 'LD26' can be printed by selecting the Scenario Output report. This report contains statistics that no other report contains. The report contains forecasted events that the simulation process generated during execution. This data is collected and stored for this report. One or many scenarios can be displayed on this report. A simple selection form opens when the report is selected from the menu pillar to allow any scenario to be included in the report, much like the Scenario Simulation Comparison report .The report contains the following information:

- Tows
- Cost
- Lock Usage
- Failures
- Delays
- Traffic Queue
- Rehab Time
- Repair Time

Scenario: SP1 **Description: Test Scenario policy 1** **Run Date: 4/9/97 12:08:18 PM**

	Average	Maximum	Minimum	Standard Deviation
NUMBER OF TOWS	1866	1866	1866	0
DELAY PER TOW	1901.34	1901.34	1901.34	0.00
TOTAL REPAIR COST	51,182.12	51,182.12	51,182.12	0.00
DELAY COST	1,351,802,765.09	1,351,802,765.09	1,351,802,765.09	0.00
MAXIMUM DELAY	4989.27	4989.27	4989.27	0.00
UPSTREAM QUEUE	6	6	6	0
DOWNSTREAM QUEUE	3	3	3	0
TIME FAILURES	0	1E-38	0	0
LOCKAGE FAILURES	2	2	2	0
TOW LOCKAGE FAILURES	24	24	24	0
% LOCK USED	47.99%	47.99%	47.99%	0.00%
% LOCK REPAIR	4.34%	4.34%	4.34%	0.00%
% LOCK REHAB	1.20%	1.20%	1.20%	0.00%
REHAB COST	6,720.22	NA	NA	NA

The final simulation report contains terse output of the scenario input data and simulation output statistics including chamber failure and chamber usage results. This report is in ASCII format and can be opened with a text editor such as Notepad. Selecting Scenario Statistics from the menu and then selecting the scenario to view opens the report. The report contains the following information:

- Scenario Input Data
- Rollup statistics
- Chamber Failure Statistics
- Chamber Usage Statistics

Model Run on:08/18/98 13:40:15

```
== Scenario Input Information ===
scenario information: scenario SP3
scenario description: Test Scenario policy 3
Iterations: 1  Duration:   5000.000
Lock: LD 26 First test cut
Number of Chambers: 2
Start Year: 1995
Base Year: 1997
Rehab Plan: REHAB2
Alpha:   1.5000
Service:      1.000
Interest:      0.085
Time Event Interval:   25.000
Annual Traffic Growth:  0.00000
Repair Policy Option: 1
Lockage Policy Option: 3
Month:  1  Arrivals:      34.00
Month:  2  Arrivals:      34.00
Month:  3  Arrivals:     145.00
Month:  4  Arrivals:     195.00
Month:  5  Arrivals:     190.00
Month:  6  Arrivals:     170.00
Month:  7  Arrivals:     195.00
Month:  8  Arrivals:     189.00
Month:  9  Arrivals:     164.00
Month: 10  Arrivals:     172.00
Month: 11  Arrivals:     172.00
Month: 12  Arrivals:      48.00
Seed1: 0
Seed2: 0
Seed3: 0
Output Controls
```

Output Statistics

	Average	SD	Max	Min
Tows	1893.0	0.000	1893.0	1893.0
Delay	-0.0	0.000	0.0	-0.0
MaxDelay	0.0	0.000	0.0	0.0
DelayCost	-5318.8	0.000	0.0	-5318.8
RepairCost	0.0	0.000	0.0	0.0
RehabCost	3840.1	0.000	3840.1	3840.1
USQueue	926.0	0.000	926.0	926.0
DSQueue	966.0	0.000	966.0	966.0

Chamber Failure Statistics

	# Time	# Lockage	#TowLockage
Main	0.0	0.0	0.0
Aux	0.0	0.0	0.0

Chamber Usage Statistics

	%Time Used	%Time In Repair	%Time In Rehab
Lock	0.000	0.000	0.000
Main	0.000	0.000	0.000
Aux	0.000	0.000	0.010

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APPENDIX C

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APPENDIX C: LEVEE REPAIR MODEL

The Levee Repair Model is a period based life-cycle system developed to provide a risk-based analysis of major rehabilitation alaternatives for levees and dikes. It was initially developed for use at Herbert Hoover Dike in the Florida everglades, and was named the Hoover Dike Decision Support System. The center of the application's purpose is to evaluate rehabilitation alternatives designed to reduce economic damage from breaching of the dike. Breaches (in the form of piping or seepage failure of portions of the dike) develop from elevated lake stage, which may be increased by effects of meteorological events such as hurricanes. Storms create localized surge in the level of the lake which, in conjunction with tailwater differential, static lake stage, and condition of the levee, may cause a breach. Improvements at to portions of Hoover Dike will provide decreased likelihood of breaching, yielding benefits in the form of reduced damages, decreased emergency repair costs, and reduction in population at risk.

Hoover Dike encircles Lake Okeechobee, a 730 square mile area in the Florida Everglades that ranges from 9 to 17 feet in depth. The lake supplies drinking water to 6 million people and irrigation to the surrounding agricultural industry. Breaches of the dike can lead to inundation of the agricultural regions located outside the levees. The Hoover Dike Decision Support System is a simulation model designed to evaluate the economic benefits associated with the rehabilitation alternatives. The tool generates estimated damages and repair costs over a 50-year life cycle.. Data collected from mulitple iterations of the simulation is used to evaluate alternative rehabilitation plans. Execution of a simulation yields a diverse set of economic, inundation, and breach data for analysis that can be viewed in graphical or report formats.

Hoover Dike Decision Support Software is a menu driven system, containing simplified data entry forms, exceptional graphics capabilities, statistical reports, and a Monte Carlo simulation process. The model is capable of simulating severe weather, calculating lake levels, and estimating damages and costs for the facility.

Due to the significant amount of data required for model operation, the system has been designed with many features to reduce some data entry. Data is organized into a Relational Database Management System to eliminate redundant entries and to mask data so that some can be entered by the application. Features such as the ability to clone data, a graphical function editor, and automated detection and entry of Stage Damage data have been incorporated to alleviate cumbersome data entry.

Unlike Hydropower Repair and Navigation Repair, the Hoover Dike system does not contain multiple facilities. This system is based upon a single dike for analysis. To demonstrate how the system works, a walkthrough of the system will be performed. The demonstration will illustrate how information is input into the system and the outputs that can be generated.

The first data to be created in the Hoover Dike system is the Period data. Period data is a breakdown of the year into subsets that vary by hurricane probability. Periods are entered by selecting Period from the Inputs menu pillar. Once the Period form opens, the following data can be entered:

- Period Number
- Name
- Days in Period
- Probability of Hurricane During Period
- Atlantic Hurricane Probability
- Gulf Hurricane Probability

There are two requirements of the Period data:

- The sum of Atlantic and Gulf hurricane probabilities must total to 1.
- The total number of day in each period should sum to 365 days.

After the periods have been established, the next set of information to be entered is the function data. It is the largest set of data in the Hoover Dike System. It is the most extensive collection of data and can consume a significant amount of time to enter. To expedite entry, several capabilities have been incorporated into the Function Management Form (Figure C-1). A function can be “Cloned” and then the data changed to save time entering data. Coordinate data points can be created, edited, and removed easily through

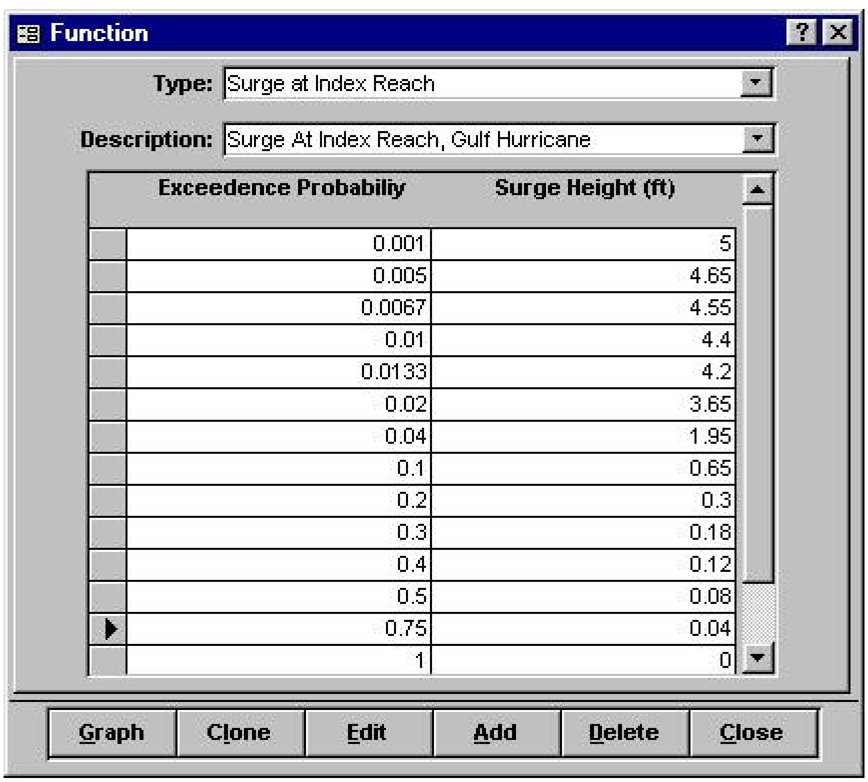


Figure C-1. Function Management Form

the interface. To create a new function, click the Add button and a form will open to enter a name, function type, and external function number. Once the function has been created, the Function form will display the data. Coordinate points are entered by typing the values into the data sheet located in the center of the form. Functions for the following function types must be entered:

- Surge at Index Reach
- Component PUP
- Damage Cell-Stage Damage
- Lake Stage Reduction
- Damage Reduction Based on Prior Period Inundation
- Reach O&M Cost

A Hoover Dike System capability that increases proficiency of data entry is the Graphical Editor (Figure C-2). The Graphical Editor displays a function with all of its data points plotted on a Cartesian coordinate system. Data points can be moved or deleted, or new points added through the use of a mouse. This routine is a very quick method for entering many points for a function.

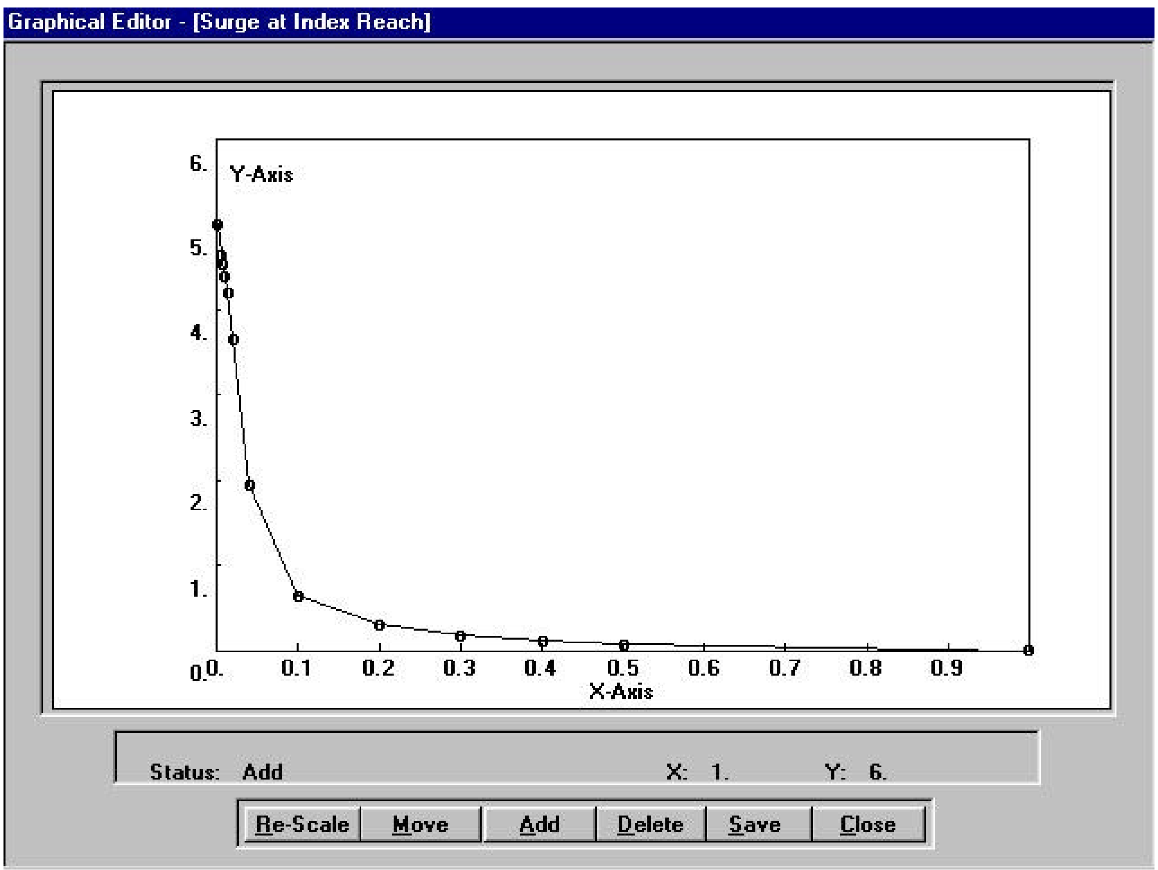


Figure C-2. Graphical Editor Form

Land Use Codes are the next element of the system to be entered. These codes are used in the determination of damage costs based on the lake level. The entry form is launched by selecting Land Use from the Inputs menu pillar. The inputs consist of the following:

- Number
- Code
- Description
- Damage Reduction Function
- Monetary Cost Option

In the Hoover Dike System, input forms have been organized so that the data required by the system is separated into logical formats that display related information. With the hierarchy of reaches, components, and damage cells in consideration, forms were created that reflect their relationships.

An excellent example of displaying relationships is the Reach Management Form (Figure C-3). It allows all of the reach specific information to be entered, along with allowing components to be created and assigned to each reach. To create a new reach for the dike, click the Add button and enter all of the necessary data. To create components for the reach, click the Component button and a form will open to create or edit the components for the current reach.

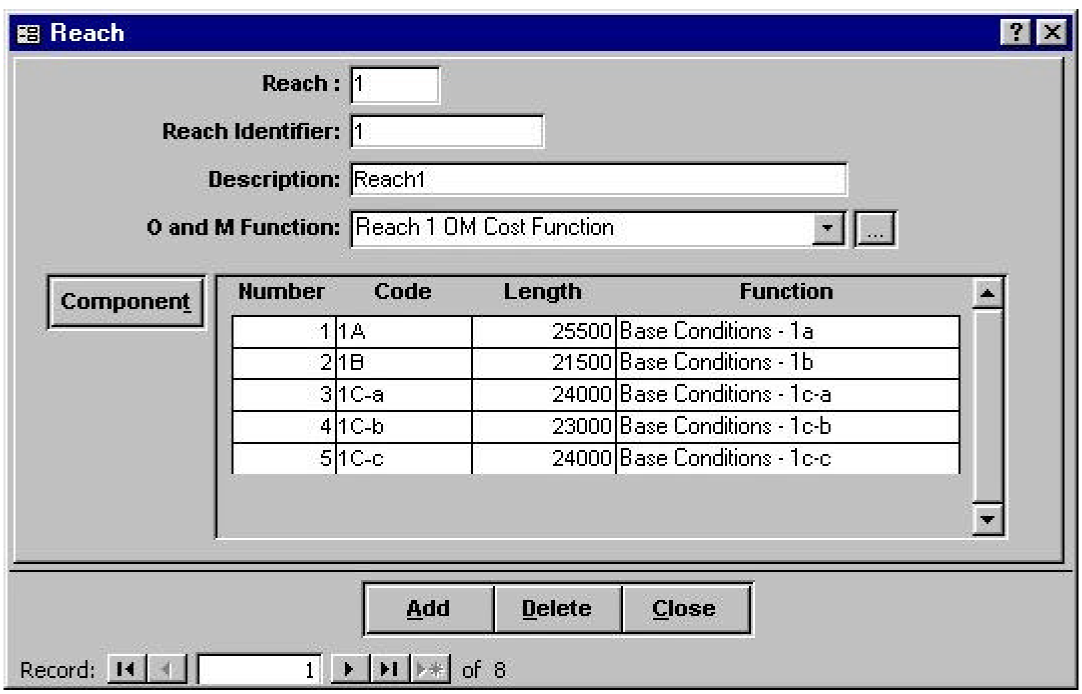
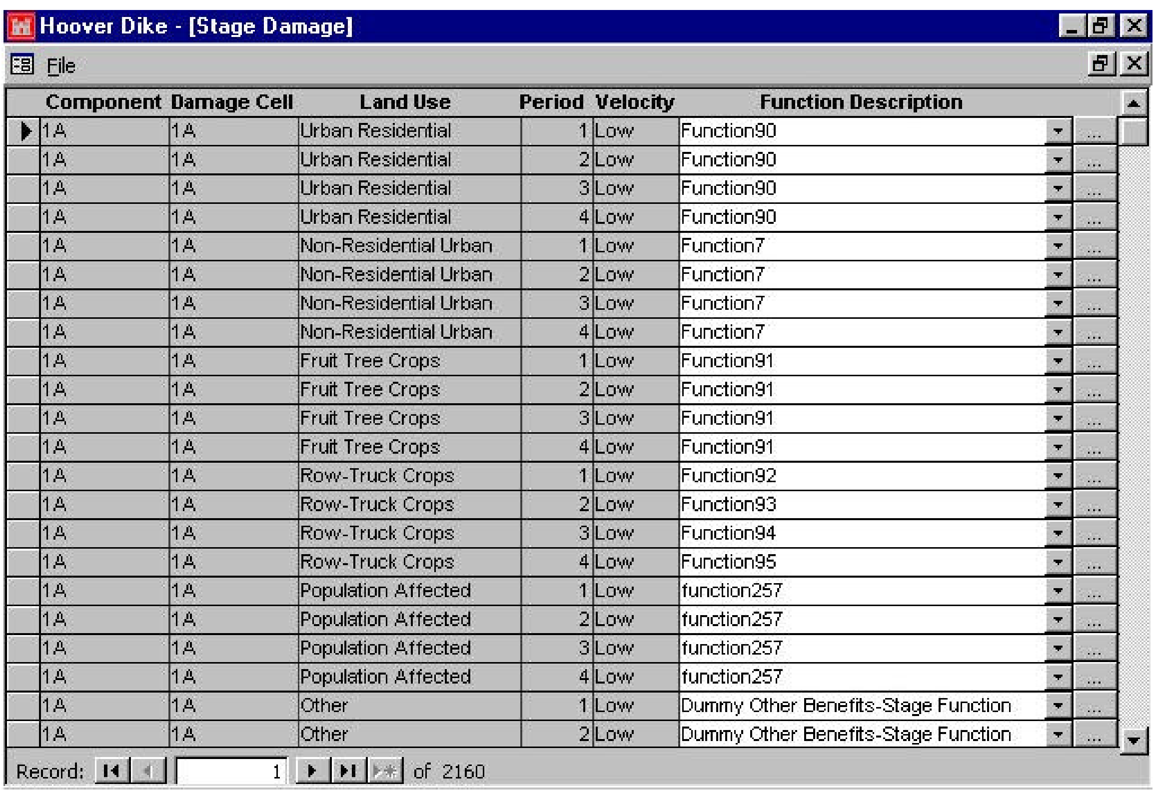


Figure C-3. Reach Management Form

Damage Cells for the dike are created and assigned to Components in the same manner as the Component data. This implementation achieves a standardization of forms, concise understanding of data, and simplex data entry. Data relationships are established through the interface, relieving confusion and additional entry by users.

The simulation process calculates the physical and economic behaviors of the dike over all time periods. For the simulation to calculate expenditures, a cost function must be assigned to every possible situation that may occur during a run. For this reason, all possible situations must be established prior to a simulation run. For any Land Use code of a Damage Cell, if a storm of a High or Low velocity occurs in a particular Time Period, the simulation needs to know how to adjust costs. These elements of the situation must be entered into the data before the Stage Damage Transitional data can be entered. The Stage Damage Management Form (Figure C-4) contains all of these possibilities and their assigned Damage Function. To speed entry, the Hoover Dike System provides a method for automating entry for all of the possibilities through a detection form. To begin this process, select Stage Damage Detect from the Inputs menu pillar. This launches an interface for detecting any records that are missing from the stage damage data. Clicking the Detect button locates and inserts all missing records. Only the Damage Cell Function will need to be entered for each record found to complete the Stage Damage data. A report of the inserted records can be printed by clicking the Print button.


Hoover Dike - [Stage Damage]
File

Component	Damage Cell	Land Use	Period	Velocity	Function Description
1A	1A	Urban Residential	1	Low	Function90
1A	1A	Urban Residential	2	Low	Function90
1A	1A	Urban Residential	3	Low	Function90
1A	1A	Urban Residential	4	Low	Function90
1A	1A	Non-Residential Urban	1	Low	Function7
1A	1A	Non-Residential Urban	2	Low	Function7
1A	1A	Non-Residential Urban	3	Low	Function7
1A	1A	Non-Residential Urban	4	Low	Function7
1A	1A	Fruit Tree Crops	1	Low	Function91
1A	1A	Fruit Tree Crops	2	Low	Function91
1A	1A	Fruit Tree Crops	3	Low	Function91
1A	1A	Fruit Tree Crops	4	Low	Function91
1A	1A	Row-Truck Crops	1	Low	Function92
1A	1A	Row-Truck Crops	2	Low	Function93
1A	1A	Row-Truck Crops	3	Low	Function94
1A	1A	Row-Truck Crops	4	Low	Function95
1A	1A	Population Affected	1	Low	function257
1A	1A	Population Affected	2	Low	function257
1A	1A	Population Affected	3	Low	function257
1A	1A	Population Affected	4	Low	function257
1A	1A	Other	1	Low	Dummy Other Benefits-Stage Function
1A	1A	Other	2	Low	Dummy Other Benefits-Stage Function

Record: 1 of 2160

Figure C-4. Stage Damage Management Form

Like Reach data, Rehabilitation Plans of the dike have a hierarchy associated with them. Each Rehab Plan has a subsequent Cost Schedule and a set of component rehabs. Each of these data sets is accessible from the Rehab Plan Management Form (Figure C-5). To create a new Rehab plan for the dike, click the Add button and enter a name and a description. To build a cost schedule, click the Cost Schedule button and a form will open to enter an effective cycle, expenditure, and purpose. Clicking the Component Rehab button launches the Component Rehab form where component level rehab data is defined.

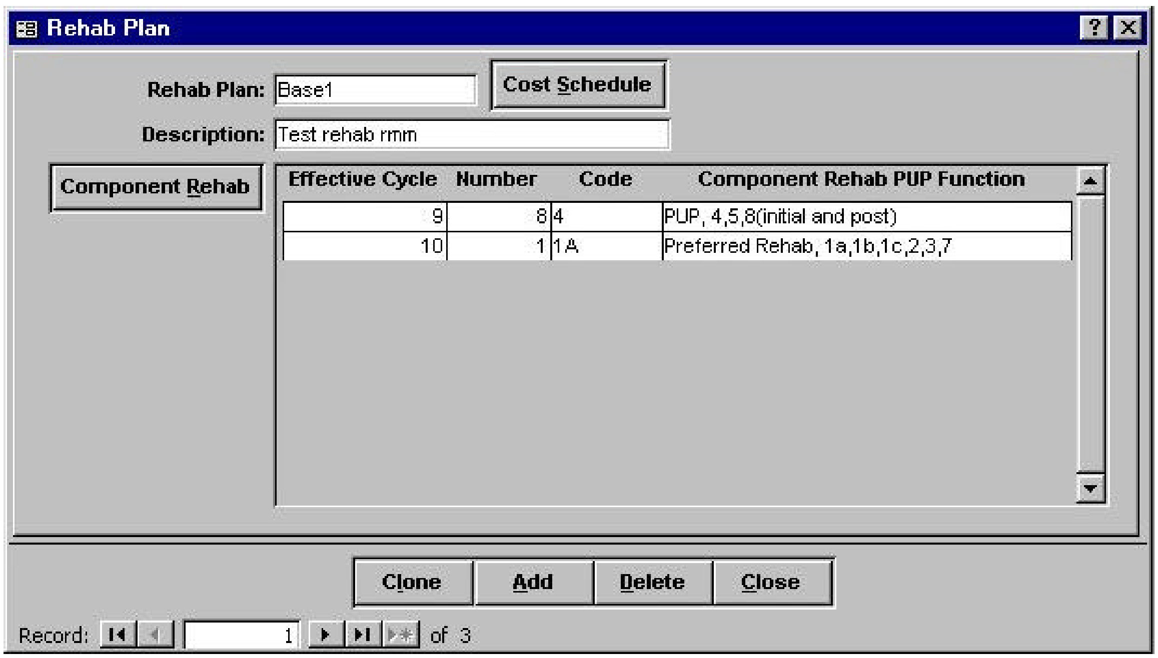


Figure C-5. Rehab Plan Management Form

The objective of the Hoover Dike System is to determine the economic impacts due to breaching of one or more reaches in response to high lake levels. This is achieved by setting up Scenarios with parameters that the simulation process requires to predict severe weather and to calculate probabilities of breaching. Factors such as simulation duration, number of iterations, and interest rate are entered into the scenario to produce accurate results and convergence of statistics. Because of the nature of the simulation process, Scenarios are cloned and only minor changes are made to generate results. To create a new scenario, locate a scenario that resembles the values which the new scenario will contain. Next click the Clone button, and the current scenario is cloned and the form displays the clone for editing. The Scenario Management Form is seen in Figure C-6.

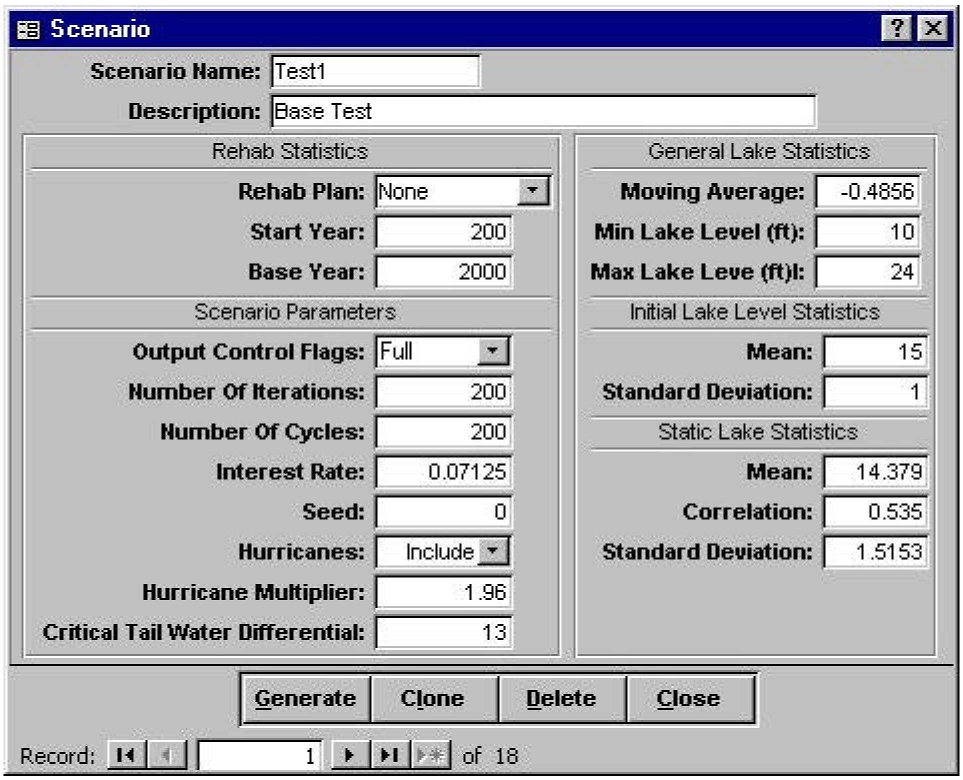


Figure C-6. Scenario Management Form

The Hoover Dike System provides two mediums for viewing simulation results: graphics and reports. The graphics are used to display raw simulation data such as frequency of component breaches, Damage Cell inundations, and iteration cost analysis. A variety of graphs can be generated and exported for use in reports. Many display settings of the graphs can be altered by clicking the right mouse button on the graph as seen in Figure C-7. More options are accessible by double clicking the graph.

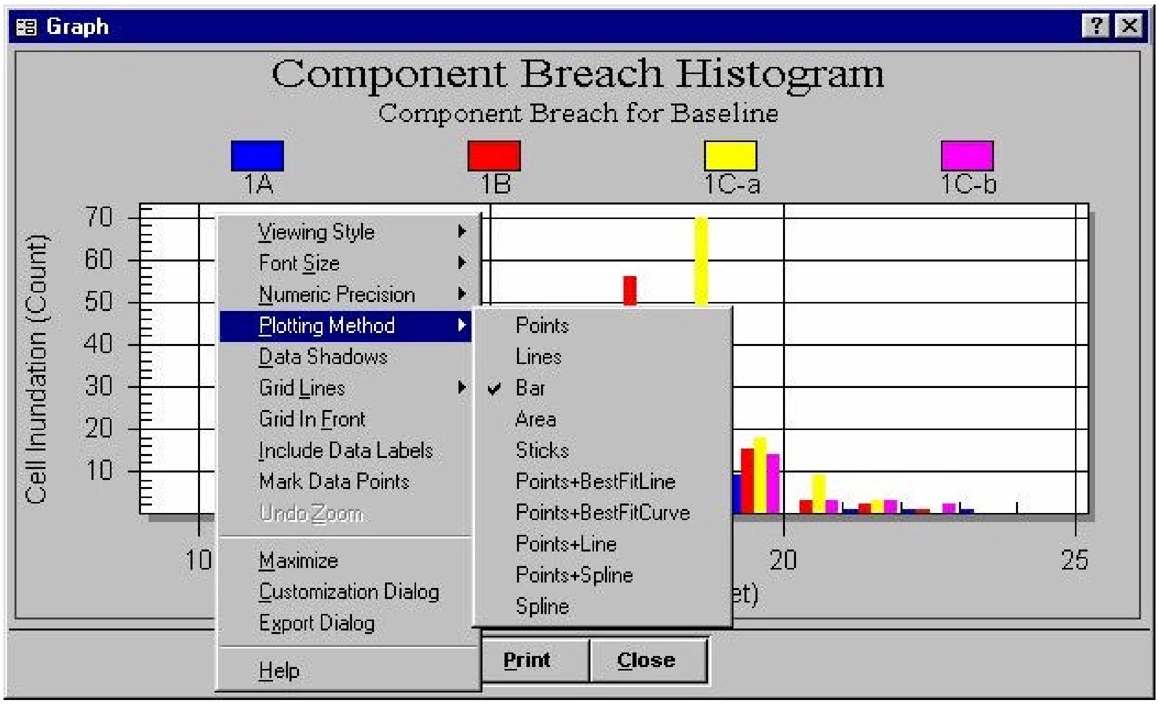


Figure C-7. Graph Settings

Reports are the primary source for viewing simulation data. There are three reports that can be printed which contain simulation statistics:

- Scenario Description Summary
- Scenario Simulation Comparison
- Scenario Land Use Results

Input data reports can be printed for a record of the data that is used to derive the results. Reach data entered for the dike can be printed in a summary or detailed report. All function data of the same type (i. e. Component PUP, Lake Stage Reduction) can be printed in reports. Each of these reports can be selected for printing by choosing the corresponding report from the Reports menu.

The Scenario Description Summary report displays Scenario input information along with the most recent cost analysis data. It is available by selecting Scenario Description Summary from the Reports menu. A scenario selection form opens to allow the user to choose which scenarios to display on the report.

Scenario: Test1 **Description:** **Run Date:**

Plan:	None	**Initial Lake Level Mean:**	15	**General Lake Statistics**		**Simulation Settings**	
Start Year:	2000	**Initital Lake Level Std Dev:**	1	**Critical Tail Water:**	13	**Iterations:**	200
Base Year:	2000	**Static Lake Level Mean:**	14.379	**Max Lake Level (ft):**	24	**Cycles:**	200
Hurricanes:	Yes	**Static Lake Correlation:**	0.535	**Min Lake Level (ft):**	10	**Interest Rate:**	0.07125
O & M Multiplier:	1	**Static Lake Std Dev:**	1.5153	**Lake Moving Average:**	-0.4856	**Seed:**	0

	Average Cost ($)	Min Cost ($)	Max Cost ($)	Std Dev	Std Error	Rehab Cost ($):	0
Repair:	588,688	0	3,506,958	632,371	44,715.4		
O && M:	28,602,530	26,538,250	31,286,631	950,884	67,237.6		
Damage:	81,622,290	0	701,026,227	88,015,551	6,223,639.3		
Total:	110,813,507			88,022,959	6,224,163.1		

Scenario: T-1000 **Description:** 1000 Iterations **Run Date:** 8/21/98 2:44:25 PM

Plan:	None	**Initial Lake Level Mean:**	15	**General Lake Statistics**		**Simulation Settings**	
Start Year:	1997	**Initital Lake Level Std Dev:**	1	**Critical Tail Water:**	13	**Iterations:**	10
Base Year:	2000	**Static Lake Level Mean:**	14.379	**Max Lake Level (ft):**	24	**Cycles:**	200
Hurricanes:	Yes	**Static Lake Correlation:**	0.535	**Min Lake Level (ft):**	10	**Interest Rate:**	0.07125
O & M Multiplier:	1	**Static Lake Std Dev:**	1.5153	**Lake Moving Average:**	-0.4856	**Seed:**	0

	Average Cost ($)	Min Cost ($)	Max Cost ($)	Std Dev	Std Error	Rehab Cost ($):	0
Repair:	839,851	0	2,795,496	922,155	291,610.9		
O && M:	34,949,223	33,803,296	36,259,059	771,873	244,087.7		
Damage:	126,273,058	0	302,220,238	106,764,933	33,762,036.4		
Total:	162,062,132			106,771,706	33,764,178.0		

Scenario: T-1000D **Description:** 1000 Iterations debug **Run Date:** 8/6/98 10:08:25 AM

Plan:	None	**Initial Lake Level Mean:**	15	**General Lake Statistics**		**Simulation Settings**	
Start Year:	1997	**Initital Lake Level Std Dev:**	1	**Critical Tail Water:**	13	**Iterations:**	1000
Base Year:	2000	**Static Lake Level Mean:**	14.379	**Max Lake Level (ft):**	24	**Cycles:**	200
Hurricanes:	Yes	**Static Lake Correlation:**	0.535	**Min Lake Level (ft):**	10	**Interest Rate:**	0.07125
O & M Multiplier:	1	**Static Lake Std Dev:**	1.5153	**Lake Moving Average:**	-0.4856	**Seed:**	0

	Average Cost ($)	Min Cost ($)	Max Cost ($)	Std Dev	Std Error	Rehab Cost ($):	0
Repair:	606,856	0	4,046,990	657,373	20,788.0		
O && M:	26,677,690	24,494,490	28,969,487	749,822	23,711.5		
Damage:	100,851,090	0	602,742,033	102,646,266	3,245,959.9		
Total:	128,135,635			102,651,110	3,246,113.1		

Hoover *Dike*

The Scenario Simulation Comparison report displays a scenario cost analysis compared against a base scenario. Repair Costs, Operation and Maintenance Costs, and Damage Costs are reported for each Scenario. Gross Benefits, Net Benefits, and the Benefit/Cost Ratio are calculated with respect to the base scenario to give a comparative analysis of costs. The base scenario has no rehab plan associated with it, while the scenarios compared to it generally were run with a rehab plan.

Scenario Simulation Comparison

02-Oct-98 *2:51 PM*

Scenario Description Date	Damage Cost Average Max/Min/STD	Repair Cost Average Max/Min/STD	O&M Cost Average Max/Min/STD	Investment Cost Average	Benefits Average STD/Error	Net Benefits Average STD/Error	B/C Ratio Average STD/Error
Base Condition							
Baseline	**$85,310,598**	**$22,353,522**	**$28,565,400**				
Baseline, new pups 6/4/98	$589,193,178	$130,167,847	$31,028,196				
8/28/98 12:13:33 PM	$0	$0	$26,639,228				
	$91,551,163	$23,716,763	$874,976				
T-10DNHR	**$85,344,748**	**$19,794,512**	**$35,222,582**	**$545,197**	**($4,132,321)**	**($4,677,518)**	**-7.579**
10 Iterations debug no hurricane	$697,622,921	$159,442,017	$38,372,511		13,542,945	13,542,945	24.840
8/28/98 12:12:40 PM	$0	$0	$32,236,731		3,268,563	3,268,563	5.995
	$105,457,502	$23,825,427	$1,025,705				
wp 8 6	**$130,858,309**	**$39,952,533**	**$34,951,220**	**$545,197**	**($69,532,541)**	**($70,077,738)**	**-127.537**
with rehab	$299,838,883	$118,546,112	$36,294,999		31,343,615	31,343,615	57.490
8/28/98 12:14:57 PM	$7,164,028	$1,436,193	$33,803,296		33,132,065	33,132,065	60.771
	$120,090,504	$37,864,719	$781,700				
Reh_A	**$24,616,032**	**$7,957,408**	**$41,681,203**	**$19,332,986**	**$61,974,879**	**$42,641,893**	**3.206**
Tailwater Control Plan	$467,814,085	$130,616,855	$60,386,019		34,294,036	34,294,036	1.774
8/28/98 12:17:41 PM	$0	$0	$28,823,322		2,424,955	2,424,955	0.125
	$57,609,170	$16,909,982	$5,413,700				

Hoover Dike

The Scenario Land Use Results Report contains a breakdown of the damage costs for each Land Use Code at every Component. The report displays the average, minimum, maximum, and standard deviation of Damage Costs calculated independently for each Scenario.

Scenario: Baseline

Component:	1A	Land Use Code	Min Value	Max Value	Average	Std Deviation
		AG	0	3,450,792	136,809	530,351
		NR	0	0	0	0
		OD	0	388,314	14,675	56,694
		PO	0	2,995	124	372
		RT	0	1,001,113	35,055	136,685
		UR	0	4,118,614	144,937	565,322
Component:	1B	**Land Use Code**	**Min Value**	**Max Value**	**Average**	**Std Deviation**
		AG	0	0	0	0
		NR	0	1,503,936	67,550	210,315
		OD	0	1,151,395	72,349	163,986
		PO	0	1,123	69	165
		RT	0	40,057,074	2,198,449	6,480,799
		UR	0	1,177,633	47,108	149,812
Component:	1C	**Land Use Code**	**Min Value**	**Max Value**	**Average**	**Std Deviation**
		AG	0	276,095	55,290	64,468
		NR	0	22,944,599	1,944,883	3,420,585
		OD	0	15,506,427	2,470,058	3,086,347
		PO	0	71,146	11,718	10,620
		RT	0	133,899,029	22,823,360	26,813,273
		UR	0	59,367,958	9,623,818	11,769,421
Component:	2	**Land Use Code**	**Min Value**	**Max Value**	**Average**	**Std Deviation**
		AG	0	5,282,640	522,161	879,796
		NR	0	3,264,066	191,974	381,999
		OD	0	15,385,655	1,809,165	2,947,849
		PO	0	23,628	3,553	4,797
		RT	0	102,976,481	11,145,979	17,646,602
		UR	0	9,836,586	962,815	1,650,473

APPENDIX D

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APPENDIX D: WATERWAY SYSTEM SIMULATION

The Waterway System Simulation, known as the Gulf Intracoastal Waterway application, is an event-driven system developed to explore the benefits of channel improvements to the overall transportation time of commodities. The main focus of the system is to investigate the improved route times from origin to destination for all commerce across the entire system due to proposed changes in the physical structure. Improvements will generate benefits by reducing vessel delay, and increasing safety.

There is a significant amount of data necessary for establishing the Waterway System that includes a full node-link system, transit rules, route information, trip parameters, and simulation setup. Before an event driven simulation can be executed, all of the information listed above must be entered. A powerful graphical interface has been developed to aid users in their efforts to input the diverse data of the system and to decrease the time needed to setup the physical waterway and transit rules so that scenarios can be generated.

To demonstrate the use of this system, a walkthrough consisting of entering the waterway system, its routes, and transit rules will be discussed. Population of the database will occur in a logical order, followed by establishing scenarios and producing analysis reports.

The heart of the model is the Link-Node network that represents all the pathways between ports in the intracostal system. The network consists of nodes and reaches. Ports are a subset of nodes at which trips originate or terminate. A graphical method of entering these components with their relationships has been created that uses the mouse as the primary tool for entering the data. This form is called the Network Builder (Figure D-1). It is used to author a waterway by creating, removing, and relocating its components. The primary purpose of the builder is to provide visual reference for reaches and ports in a study area.

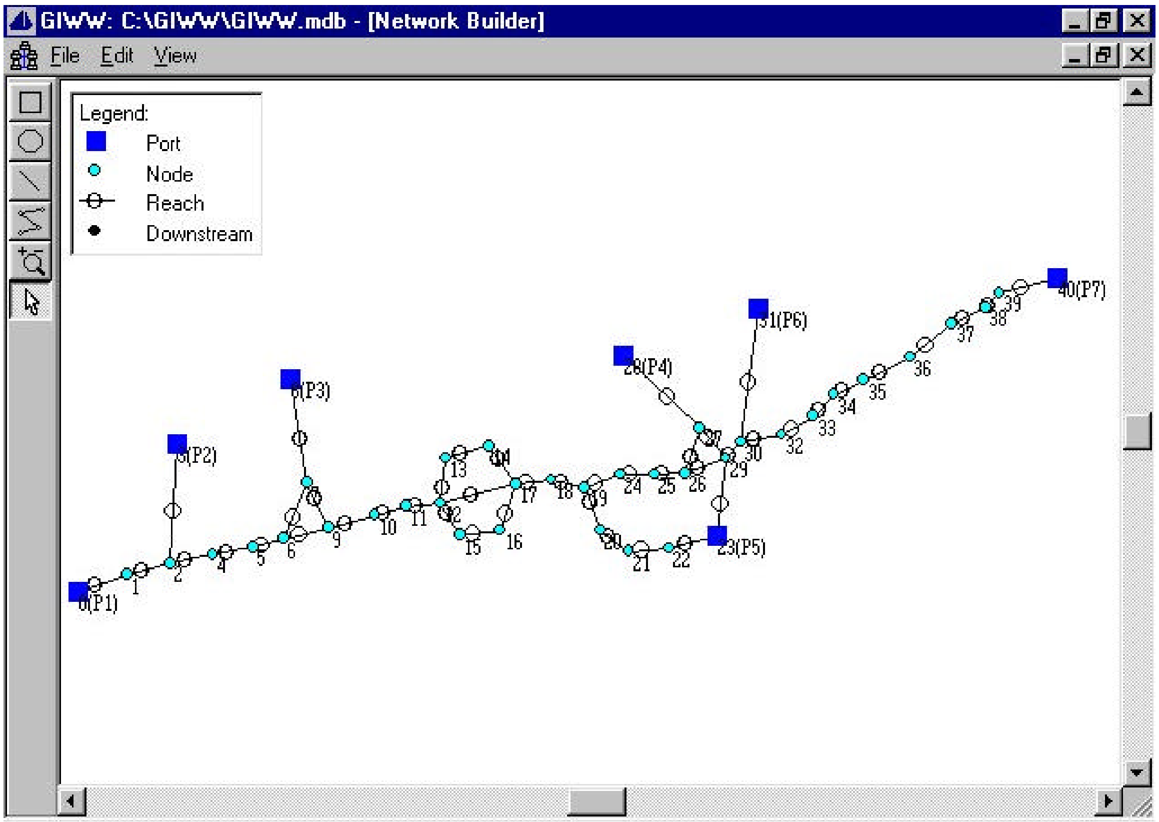


Figure D-1. Network Builder

In addition, the builder incorporates the ability to create routes. A route is a path through the network from origin to destination. In a short amount of time, a network system along with a scheme of routes can be assembled. A toolbar technique for selection of modes makes the interface a productive instrument of the application.

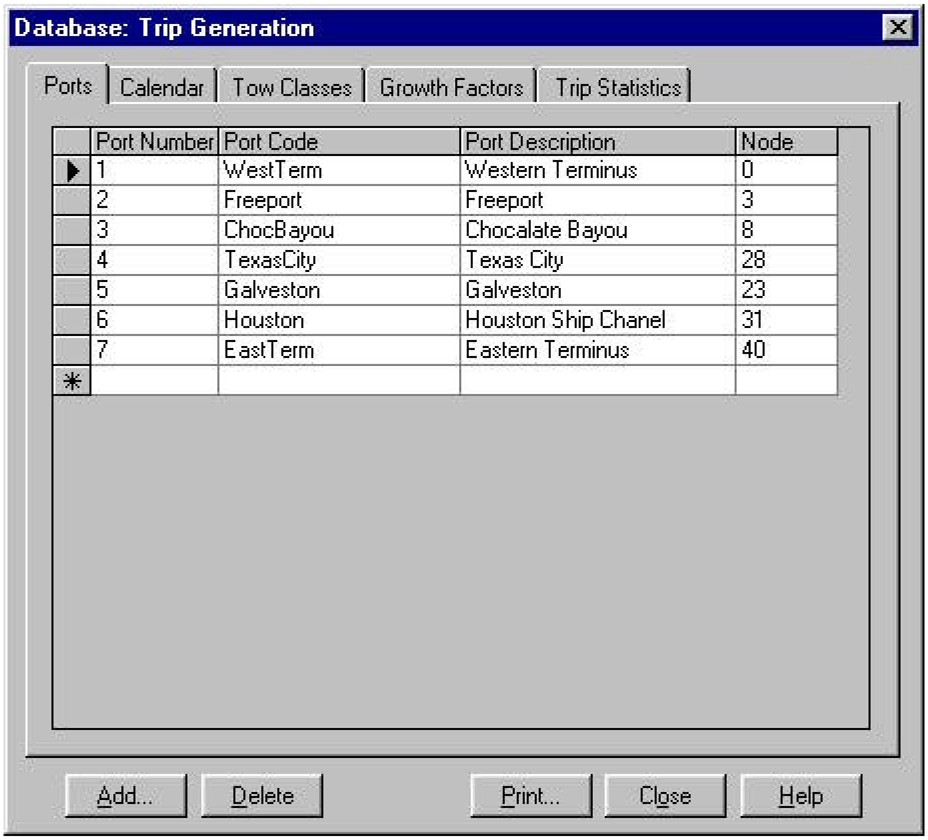
Ports are the first component of the waterway to be created. They are established by entering the Add Port mode and clicking the mouse everywhere that a port exists. Next, nodes are added to the waterway by entering the Add Node mode and clicking the graph where a node is desired. Once ports and nodes appear on the graph, the reaches between them can be added. Reaches are added by entering the Add Reach mode, clicking the upstream node then clicking the downstream node. A path is drawn with a dot located adjacent to the downstream node. Nodes and ports can be relocated by clicking and dragging them to a desired location. Properties of each component are accessible by positioning the cursor above and performing a right mouse click.

Once the waterway has been established, traffic routes can be created. Routes are created by entering the Add Route mode and clicking each node in its path. The route begins with the origin port and is followed by every node in the path until the destination port is reached. Once all of the reaches in the path have been selected, the route can be added by right mouse clicking and selecting ‘Finish selecting reaches and add the new route’.

The other data entry forms in the application display a spreadsheet view of the data. There are four input data forms and one simulation input form that comprise the remainder of the system. The forms are:

- Trip Generation Form
- Network Form
- Reach Transit Form
- Route Form
- Scenario Form

The Trip Generation Form (Figure D-2) contains information that applies to the Port-to-Port level of the simulation. Here, diverse information is supplied for the system on a ‘Tab’ form. Ports are displayed on the first tab. The second tab contains a calendar of time periods. The third tab is used to create tow classes by cost. On the fourth tab, port to port traffic growth factors are entered. The final tab contains a mean and standard deviation for trips for each possible port to port transaction by period. Data is entered for each of these through a spreadsheet interface.



Database: Trip Generation

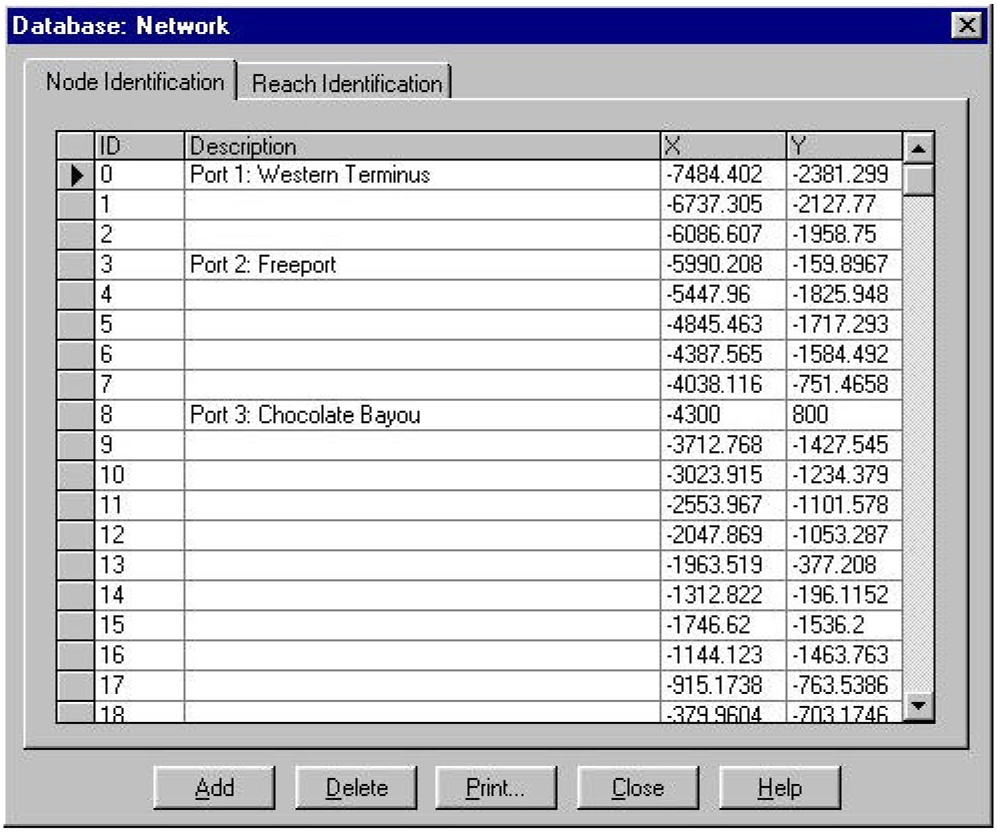
Ports | Calendar | Tow Classes | Growth Factors | Trip Statistics

Port Number	Port Code	Port Description	Node
1	WestTerm	Western Terminus	0
2	Freeport	Freeport	3
3	ChocBayou	Chocalate Bayou	8
4	TexasCity	Texas City	28
5	Galveston	Galveston	23
6	Houston	Houston Ship Chanel	31
7	EastTerm	Eastern Terminus	40

Add... Delete Print... Close Help

Figure D-2. Trip Generation Form

The Network Form (Figure D-3) contains a spreadsheet view of the Network Builder. All nodes in the waterway system including reach data can be entered or edited from this form. Editing values from this form provides concise values for the graphical information that the builder displays. Although Node and Reach data can be changed through this form, the best means for altering information is through the use of the Network Builder.


Database: Network

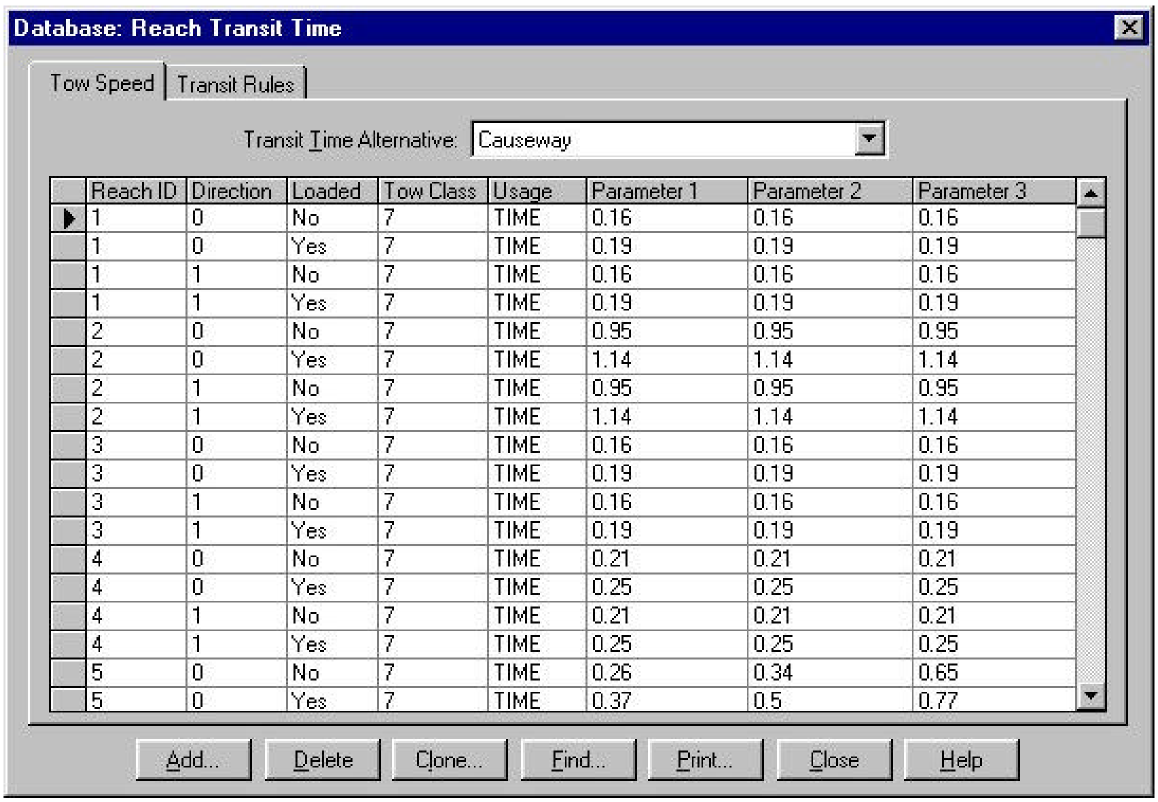
Node Identification | Reach Identification

ID	Description	X	Y
0	Port 1: Western Terminus	-7484.402	-2381.299
1		-6737.305	-2127.77
2		-6086.607	-1958.75
3	Port 2: Freeport	-5990.208	-159.8967
4		-5447.96	-1825.948
5		-4845.463	-1717.293
6		-4387.565	-1584.492
7		-4038.116	-751.4658
8	Port 3: Chocolate Bayou	-4300	800
9		-3712.768	-1427.545
10		-3023.915	-1234.379
11		-2553.967	-1101.578
12		-2047.869	-1053.287
13		-1963.519	-377.208
14		-1312.822	-196.1152
15		-1746.62	-1536.2
16		-1144.123	-1463.763
17		-915.1738	-763.5386
18		-379.9604	-703.1746

Add | Delete | Print... | Close | Help

Figure D-3. Network Form

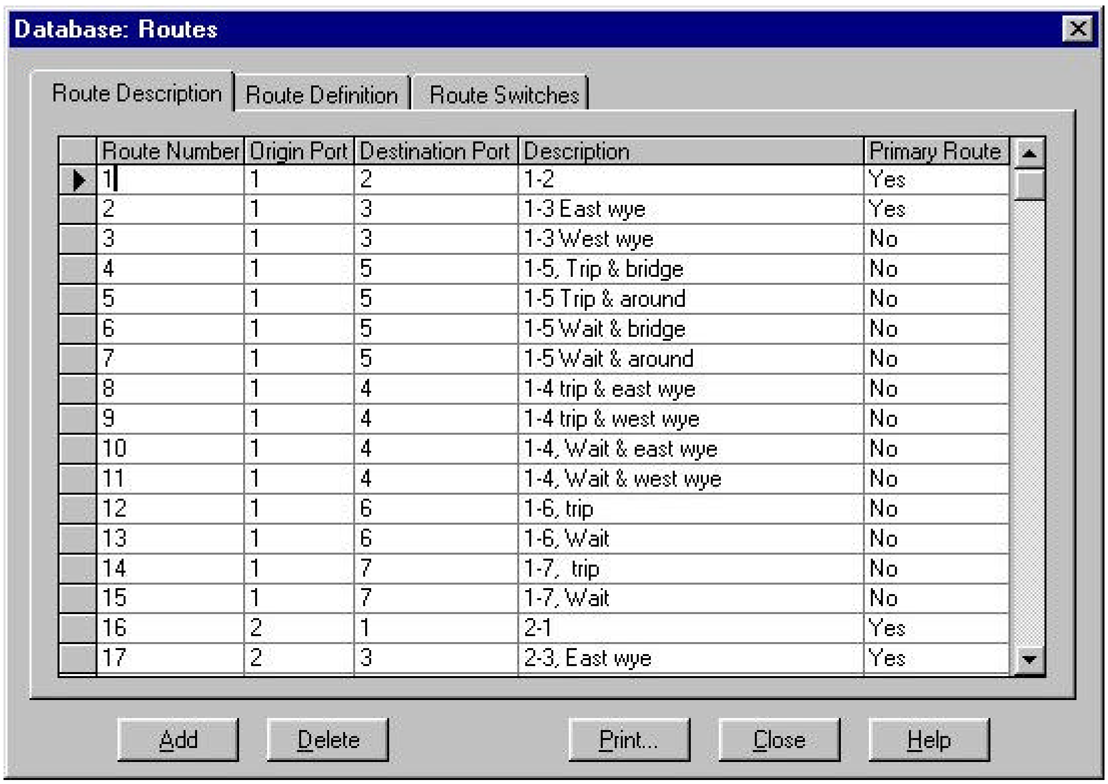
In the Reach Transit Form (Figure D-4), parameters are entered that allow the simulation process to determine how vessels interact with each other while accompanying the same reach. Interactions between vessels usually follow one of the following rules: no limitations, no overtaking in same direction, no meeting, or single vessel only. Depending upon the particular transit rule in effect for a reach, the exit time for a tow will be change based on other tows in the reach to preserve the appropriate queuing behavior within the reach. Transit rules are applied to all tows in the reach, independent of tow type and direction.



Reach ID	Direction	Loaded	Tow Class	Usage	Parameter 1	Parameter 2	Parameter 3
1	0	No	7	TIME	0.16	0.16	0.16
1	0	Yes	7	TIME	0.19	0.19	0.19
1	1	No	7	TIME	0.16	0.16	0.16
1	1	Yes	7	TIME	0.19	0.19	0.19
2	0	No	7	TIME	0.95	0.95	0.95
2	0	Yes	7	TIME	1.14	1.14	1.14
2	1	No	7	TIME	0.95	0.95	0.95
2	1	Yes	7	TIME	1.14	1.14	1.14
3	0	No	7	TIME	0.16	0.16	0.16
3	0	Yes	7	TIME	0.19	0.19	0.19
3	1	No	7	TIME	0.16	0.16	0.16
3	1	Yes	7	TIME	0.19	0.19	0.19
4	0	No	7	TIME	0.21	0.21	0.21
4	0	Yes	7	TIME	0.25	0.25	0.25
4	1	No	7	TIME	0.21	0.21	0.21
4	1	Yes	7	TIME	0.25	0.25	0.25
5	0	No	7	TIME	0.26	0.34	0.65
5	0	Yes	7	TIME	0.37	0.5	0.77

Figure D-4. Reach Transit Form

The Route Form (Figure D-5) contains all of the routes that have been established for the waterway model. Once a route has been established via the Network Builder, it can be accessed and altered through this form. The route chooser stores the probability that a tow of a particular tow type will choose a given route between ports. The user can set the probability of the tow moving along each route - but the sum of route probabilities between a given port pair for a tow type must equal 1.0. When a particular tow enters the waterway system, the model chooses the particular route taken to the destination port based on the stored probabilities.


Database: Routes

Route Description | Route Definition | Route Switches

Route Number	Origin Port	Destination Port	Description	Primary Route
1	1	2	1-2	Yes
2	1	3	1-3 East wye	Yes
3	1	3	1-3 West wye	No
4	1	5	1-5, Trip & bridge	No
5	1	5	1-5 Trip & around	No
6	1	5	1-5 Wait & bridge	No
7	1	5	1-5 Wait & around	No
8	1	4	1-4 trip & east wye	No
9	1	4	1-4 trip & west wye	No
10	1	4	1-4, Wait & east wye	No
11	1	4	1-4, Wait & west wye	No
12	1	6	1-6, trip	No
13	1	6	1-6, Wait	No
14	1	7	1-7, trip	No
15	1	7	1-7, Wait	No
16	2	1	2-1	Yes
17	2	3	2-3, East wye	Yes

Add | Delete | Print... | Close | Help

Figure D-5. Route Form

Scenarios contain parameters that the simulation process requires to emulate traffic behavior on the waterway system. Waterway data, simulation parameters, and output control flags are set on this form. The model simulates behavior for a user-specified duration in hours. The user can set the number and length of periods within a year to reflect different traffic patterns in the waterways at different times of the year. In order to allow for start up of the simulation, a user can input a conditioning period (number of hours), to allow tows to populate the waterway, before starting the actual simulation, for which output statistics are collected. Other capabilities that are available on the Scenario Editor Form (Figure D-6) are the abilities to create, edit, clone, remove, and print scenario information. In addition, a verification procedure on the input data can be performed.

Figure D-6. Scenario Editor Form

The GIWW system contains many reports that display the results of processed scenarios. In addition to ASCII files that the simulation generates, three other reports are available for displaying results:

- Scenario-Reach Comparison Report
- Scenario Description Report
- Scenario Comparison Report

Clicking the ‘SRR’ button located on the application toolbar and selecting scenarios to display previews the Scenario Reach-Comparison Report (SRR). This report allows the user to compare scenarios results by reach. This is especially useful in identifying reaches for further incremental analysis. Because of possible system effects, care must be taken to evaluate each improvement separately as well as in combinations. In addition, some improvements may affect traffic and transportation costs in more than one reach by providing an alternative route. Construction at a reach changes tows, times, and costs in several reaches. Although the transportation cost in a reach increases, the increase could be offset by reductions in other reaches. The report contains a comparison of the following information:

- Average and Standard Deviation of Number of Tows
- Average and Standard Deviation of Hours of Tows
- Average and Standard Deviation of Cost of Tows

Reach: 1

	Average Tows	SD Tows	Average Hours	SD Hours	Average Cost	SD Cost
Causeway_1998	793.900	36.561	141.114	6.759	$21,164.97	$984.80
Causeway_2005	850.167	33.768	151.158	6.160	$22,666.78	$905.43
Transportation Change	-56.267	2.793	-10.044	0.599	$-1,501.81	$79.37
Causeway_1998	793.900	36.561	141.114	6.759	$21,164.97	$984.80
Causeway_2015	941.867	41.273	167.585	7.263	$25,116.77	$1,095.94
Transportation Change	-147.967	-4.712	-26.471	-0.504	$-3,951.80	$-111.14

Reach: 2

	Average Tows	SD Tows	Average Hours	SD Hours	Average Cost	SD Cost
Causeway_1998	794.767	36.524	844.316	40.425	$126,600.38	$5,890.49
Causeway_2005	850.700	33.987	904.020	37.173	$135,523.77	$5,455.22
Transportation Change	-55.933	2.537	-59.704	3.251	$-8,923.39	$435.27
Causeway_1998	794.767	36.524	844.316	40.425	$126,600.38	$5,890.49
Causeway_2015	942.567	41.428	1,002.402	43.568	$150,195.27	$6,568.19
Transportation Change	-147.800	-4.904	-158.086	-3.143	$-23,594.88	$-677.70

Reach: 3

	Average Tows	SD Tows	Average Hours	SD Hours	Average Cost	SD Cost
Causeway_1998	269.700	23.202	47.255	4.004	$7,162.85	$613.96
Causeway_2005	290.467	28.352	50.947	5.014	$7,716.54	$754.55
Transportation Change	-20.767	-5.150	-3.693	-1.010	$-553.69	$-140.59
Causeway_1998	269.700	23.202	47.255	4.004	$7,162.85	$613.96
Causeway_2015	319.067	31.884	55.938	5.716	$8,475.76	$850.25
Transportation Change	-49.367	-8.682	-8.683	-1.712	$-1,312.91	$-236.29

Reach: 4

	Average Tows	SD Tows	Average Hours	SD Hours	Average Cost	SD Cost
Causeway_1998	1,002.067	47.736	233.477	11.256	$35,091.92	$1,674.69
Causeway_2005	1,075.467	49.368	250.668	11.689	$37,668.34	$1,732.18
Transportation Change	-73.400	-1.632	-17.191	-0.433	$-2,576.42	$-57.50
Causeway_1998	1,002.067	47.736	233.477	11.256	$35,091.92	$1,674.69
Causeway_2015	1,188.833	50.583	277.245	12.023	$41,646.54	$1,785.23
Transportation Change	-186.767	-2.847	-43.768	-0.767	$-6,554.62	$-110.54

Reach: 5

	Average Tows	SD Tows	Average Hours	SD Hours	Average Cost	SD Cost
Causeway_1998	1,002.200	47.747	492.620	24.119	$73,832.69	$3,564.65
Causeway_2005	1,075.533	49.363	529.378	24.713	$79,323.83	$3,644.72
Transportation Change	-73.333	-1.616	-36.757	-0.594	$-5,491.14	$-80.07

The Scenario Description Report (SDR) provides all the information about a scenario shown on the Scenario Editor dialogue box. In addition, it provides a date stamp for the run, the version of the C++ kernel, and the computation time. Simulation results are shown in the bottom portion of the report. The values shown are the statistics for tows, transit hours and transit costs for the entire system for the scenario.

Scenario Summary

Scenario	Scenario Description
Causeway_1998	Causeway, base year 1 month

Trip Alternative	Transit Time Alternative	Route Choice Alternative	Period Alternative	Transit Rule Alternative
OneYear	Causeway	Without	Year	NoRules

Simulation Length	Iterations	Interest Rate	Start Year	Base Year	No Overtaking Time	Conditioning Hours
750.000	30	7.12%	1998	1998	0.100	20.000

Congestion SD Factor	Growth Factor	Seed	Run Date	Kernel Version	Computation Time (sec)
1.000	1.000	17	1998/04/11 22:44:15.00	0.990	577.00

Simulation Results

Average Tows	SD Tows	Minimum Tows	Maximum Tows
1,724.367	47.458	1,625.000	1,834.000

Average Hours	SD Hours	Minimum Hours	Maximum Hours
21,494.351	854.733	19,226.624	23,972.924

Average Cost	SD Cost	Minimum Cost	Maximum Cost
$3,232,033.01	$126,131.39	$2,900,535.38	$3,592,794.55

The Scenario Comparison Report (SCR) allows the user to compare the summary results of different scenarios. The user must choose the Base Scenario with which all other selected scenarios are compared. Once the Base Scenario is chosen, the user can check the boxes of as many scenarios as are available for comparison. The difference of each selected scenario and the base scenario are displayed for each statistic on the report.

	Average Tows	SD Tows	Average Hours	SD Hours	Average Cost	SD Cost
Causeway_1998	1,724.367	47.458	21,494.351	854.733	$3,232,033.01	$126,131.39
Causeway_1998	1,724.367	47.458	21,494.351	854.733	$3,232,033.01	$126,131.39
Transportation Change	0.000	0.000	0.000	0.000	$0.00	$0.00

	Minimum Tows	Maximum Tows	Minimum Hours	Maximum Hours	Minimum Cost	Maximum Cost
Causeway_1998	1,625.000	1,834.000	19,226.624	23,972.924	$2,900,535.38	$3,592,794.55
Causeway_1998	1,625.000	1,834.000	19,226.624	23,972.924	$2,900,535.38	$3,592,794.55
Transportation Change	0.000	0.000	0.000	0.000	$0.00	$0.00

	Average Tows	SD Tows	Average Hours	SD Hours	Average Cost	SD Cost
Causeway_1998	1,724.367	47.458	21,494.351	854.733	$3,232,033.01	$126,131.39
Causeway_2005	1,845.233	51.346	23,054.414	773.057	$3,467,285.81	$113,716.53
Transportation Change	-120.866	-3.888	-1,560.063	81.676	$-235,252.80	$12,414.86

	Minimum Tows	Maximum Tows	Minimum Hours	Maximum Hours	Minimum Cost	Maximum Cost
Causeway_1998	1,625.000	1,834.000	19,226.624	23,972.924	$2,900,535.38	$3,592,794.55
Causeway_2005	1,758.000	1,962.000	21,767.116	24,977.405	$3,273,869.70	$3,745,195.41
Transportation Change	-133.000	-128.000	-2,540.492	-1,004.481	$-373,334.32	$-152,400.86

	Average Tows	SD Tows	Average Hours	SD Hours	Average Cost	SD Cost
Causeway_1998	1,724.367	47.458	21,494.351	854.733	$3,232,033.01	$126,131.39
Causeway_2015	2,032.167	53.962	25,406.172	813.050	$3,819,614.28	$120,936.43
Transportation Change	-307.800	-6.504	-3,911.821	41.683	$-587,581.27	$5,194.96

	Minimum Tows	Maximum Tows	Minimum Hours	Maximum Hours	Minimum Cost	Maximum Cost
Causeway_1998	1,625.000	1,834.000	19,226.624	23,972.924	$2,900,535.38	$3,592,794.55
Causeway_2015	1,930.000	2,148.000	23,912.454	27,695.575	$3,592,548.69	$4,159,231.67
Transportation Change	-305.000	-314.000	-4,685.830	-3,722.651	$-692,013.31	$-566,437.12

	Average Tows	SD Tows	Average Hours	SD Hours	Average Cost	SD Cost
Causeway_1998	1,724.367	47.458	21,494.351	854.733	$3,232,033.01	$126,131.39
Causeway_2025	2,238.867	63.055	27,899.382	1,016.403	$4,195,441.20	$151,239.80
Transportation Change	-514.500	-15.597	-6,405.031	-161.670	$-963,408.19	$-25,108.41

	Minimum Tows	Maximum Tows	Minimum Hours	Maximum Hours	Minimum Cost	Maximum Cost
Causeway_1998	1,625.000	1,834.000	19,226.624	23,972.924	$2,900,535.38	$3,592,794.55
Causeway_2025	2,131.000	2,389.000	26,193.492	30,819.807	$3,941,016.75	$4,625,395.61
Transportation Change	-506.000	-555.000	-6,966.868	-6,846.883	$-1,040,481.37	$-1,032,601.06

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13. ABSTRACT (Maximum 200 words)

The Institute for Water Resources (IWR) of the US Army Corps of Engineers, through research and partnership with Corps Districts, has developed a set of tools and techniques to support risk-based economic evaluations involving decisions related to major rehabilitation and maintenance investments.

Desktop computer models have been developed and applied in the areas of:

- Rehabilitation of hydropower facilities
- Rehabilitation of navigation locks
- levee/dike performance
- Commodity transport on waterways.

The models provide a framework for developing and storing required data, performing the needed calculations, evaluating results, and comparing with- and without-project alternatives from a benefit/cost perspective. The models are more general, easier to use and understand, and significantly faster than previously available methods, and can easily be directly applied or adapted to many problems.

IWR-developed the suite of models to implement complex simulation solutions in as simple a manner as possible, consistent with the nature of the problem under analysis. All of the models share a common approach and architecture. Experience in development and application of these models has provided IWR with a strong background, experience, skill and tool set in dealing with problems associated with risk-based analysis of investment decisions.

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